Development of Performance Related Specifications for Asphalt Pavements in the State of Arizona

Final Report 402-2

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16. Abstract

This report presents an Executive Summary of a comprehensive study conducted by ASU regarding a series of 11 separate projects relating to the implementation of the ME-PDG (developed under NCHRP 1-37A and NCHRP 1-40D)for the state of Arizona.

The individual study project reports deal with the characterization of a variety of AC Binder types used by ADOT (Project 2); characterization results of E* Master Curve results for typical AC mixtures used in Arizona (Project 3); the characterization of these typical ac Mixtures for Thermal Fracture (Project 4), Permanent Deformation (Project 5), and Load associated Fatigue (Project 6).In addition, recommendations are made in Project 7 regarding the implementation of the SPT for AC Mixtures.

Projects 8&9 focus on unbound bases/subbases and subgrades. Project 8 describes the results on non-linear Mr response on as variety of typiczal unbound bases and subgrades. Project 9 deals with the development of an unbound material permanent deformation database and development of a more universal permanent strain model.

In the Project 10 study report, the state of Arizona has been subdivided , on the basis of relatively unique climatic regions based upon regional geomorphology. A total of 10 climatice regions in Arizona have been developed and a listing of current EICM weather stations found in the ME-PDG are identified by climatic region.

Finally, Project 11 is a very comprehensive report study of the existing ADOT traffic files for eventual inclusion with the ME-PDG. A computerized (spreadsheet) traffic database of the entire ADOT highway networkwas conducted.

This database incorporates every mile of the Arizona highway network(6 Interstates; 13 U.S.Highways and 86 state highways). Four significant traffic factors are included in the database: Average Annual Daily Traffic (AADT), Annual Growth Rate (rg), Percent Trucks (pt), and Vehicle Classification Percentage (VCP). Relatively homogeneous traffic units were selected based on existing ADOT HPMS and VCP stations.

17. Key Words
ME-PDG; AC Binder;E* Test results; AC Thermal Fracture response; Permanent Deformation response; SPT Implemetation, Unbound Materials Mr response; Permanent Strain Model; regional State Climatic Regions; and Traffic Analysis

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS					APPROXIMATE CONVERSIONS FROM SI UNITS				
Symbol	When You Know	Multiply By	To Find	Symbol	Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH					**LENGTH**		
in	inches	25.4	millimeters	mm	mm	millimeters	0.039	inches	in
ft	feet	0.305	meters	m	m	meters	3.28	feet	ft
yd	yards	0.914	meters	m	m	meters	1.09	yards	yd
mi	miles	1.61	kilometers	km	km	kilometers	0.621	miles	mi
		AREA					**AREA**		
in^2	square inches	645.2	square millimeters	mm^2	mm^2	Square millimeters	0.0016	square inches	in^2
ft^2	square feet	0.093	square meters	m^2	m^2	Square meters	10.764	square feet	ft^2
yd^2	square yards	0.836	square meters	m^2	m^2	Square meters	1.195	square yards	yd^2
ac	acres	0.405	hectares	ha	ha	hectares	2.47	acres	ac
mi^2	square miles	2.59	square kilometers	km^2	km^2	Square kilometers	0.386	square miles	mi^2
		VOLUME					**VOLUME**		
fl oz	fluid ounces	29.57	milliliters	mL	mL	milliliters	0.034	fluid ounces	fl oz
gal	gallons	3.785	liters	L	L	liters	0.264	gallons	gal
ft^3	cubic feet	0.028	cubic meters	m^3	m^3	Cubic meters	35.315	cubic feet	ft^3
yd^3	cubic yards	0.765	cubic meters	m^3	m^3	Cubic meters	1.308	cubic yards	yd^3
	NOTE: Volumes greater than 1000L shall be shown in m^3.								
		MASS					**MASS**		
oz	ounces	28.35	grams	g	g	grams	0.035	ounces	oz
lb	pounds	0.454	kilograms	kg	kg	kilograms	2.205	pounds	lb
T	short tons (2000lb)	0.907	megagrams (or "metric ton")	mg (or "t")	mg	megagrams (or "metric ton")	1.102	short tons (2000lb)	T
		TEMPERATURE (exact)					**TEMPERATURE (exact)**		
˚F	Fahrenheit temperature	5(F-32)/9 or (F-32)/1.8	Celsius temperature	˚C	˚C	Celsius temperature	1.8C + 32	Fahrenheit temperature	˚F
		ILLUMINATION					**ILLUMINATION**		
fc	foot candles	10.76	lux	lx	lx	lux	0.0929	foot-candles	fc
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2	cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE AND PRESSURE OR STRESS					**FORCE AND PRESSURE OR STRESS**		
lbf	poundforce	4.45	newtons	N	N	newtons	0.225	poundforce	lbf
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa	kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380

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INTRODUCTION

This report summarizes the final results of Arizona Department of Transportation (ADOT) State Planning and Research (SPR) Project 402-2 *Development of Performance Related Specifications for Asphalt Pavements in the State of Arizona*, which was initiated in 1999. These specifications were to be based upon the Mechanistic-Empirical Pavement Design Guide (M-E PDG) developed for the National Cooperative Highway Research Program (NCHRP) Project 1-37A.

The overall research was divided into three major phases. Work in Phase I focused upon the development of the work plan. The work in Phase II focused on the development of the typical M-E PDG design input parameters, associated with hot mix asphalt concrete (HMAC) materials, unbound base/subgrade materials, environmental and traffic parameters for Arizona conditions. Phase III was to focus on the development of performance related asphalt specifications for Arizona. However, due to problems associated with the National U.S. Calibration of the M-E PDG, Phase III was never completed.

Report Organization

This report consists of a summary of the results of the research and appendixes that document each of the completed projects.

Phase I had one project: the work plan.

Phase II: Characterization of Arizona Department of Transportation (ADOT) materials was subdivided into ten projects (Project 2 to Project 11). These were:

Project 2: ADOT Asphalt Concrete (AC) Binder Characterization Database
Project 3: ADOT AC Mix Stiffness Characterization Database
Project 4: ADOT AC Thermal Fracture Characterization
Project 5: ADOT AC Mix Permanent Deformation Database
Project 6: ADOT AC Fatigue Characterization Database
Project 7: ADOT Implementation of Simple Performance Test
Project 8: ADOT Unbound Materials Modulus Database
Project 9: ADOT Unbound Materials Permanent Deformation Database and Development of Universal Permanent Strain Model
Project 10: Implementing the Enhanced Integrated Climatic Model (EICM) for Arizona Climatic Conditions
Project 11: Development of Design Guide Traffic Files for ADOT.

It is to be called to the reader's attention that Projects 3 through 7 dealt with a wide range of AC mixture characterization parameters. Collectively, numerous AC mix types have been referenced/analyzed in Projects 3, 4, 5, 6, and 7.

However, common to each study report, a series of eleven typical ADOT conventional lab blended AC mixtures using five different aggregates were used. They were:

> Salt River Base Mix: 3 Lab blends with Performance Grade (PG)64-22, PG76-16 and PG20-10 and Salt River Base Aggregates
>
> Salt River 3/4" Mix: Same 3 PG binder grades noted above along with Salt River 3/4" Aggregates
>
> Bidahouchi Base Mix: 2 Lab blends with PG58-28 and PG64-22, using Bidahouchi Base Aggregates
>
> Bidahouchi 3/4" Mix: 2 Lab blends with PG58-28 and PG64-22, using Bidahouchi 3/4" Aggregates
>
> Two Guns-Dennison Mix: 1 Lab blend with PG64-22 using a Superpave mix gradation.

The combination of using typical ADOT binder, along with typical ADOT mixture provided an excellent cross reference of typical ADOT asphalt mixes used in practice. All of the mixtures were typically lab blended and then compacted to a range of volumetric properties. It is recommended that the reader refer to the specific mix properties summarized in each separate project report to obtain typical mixture properties of all specimens investigated.

This report gives a summary of the project results and provides recommendations for the implementation of the new NCHRP / AASHTO M-E Pavement Design Guide. More detailed information is given in unpublished appendixes available at the Arizona Transportation Research Center Library.

BRIEF PROJECT STUDY OVERVIEW

The following paragraphs present a brief introduction of the objectives and results of each specific project. The following chapters summarize the results of the projects.

Project 1: *Development of Work Plan* had the objective to present the overall, multi-year research program with eventually developing a set of performance related specifications for asphalt pavements in the state of Arizona.

Project 2: *ADOT AC Binder Characterization Database*, provides ADOT with a database of Superpave-AASHTO properties for six typical AC binders commonly used in ADOT construction projects of HMA pavements. The main binder properties evaluated at four different aging conditions were: penetration, softening point, absolute viscosity, kinematic viscosity, flexural creep stiffness parameters, complex shear modulus, phase angle, and ultimate tensile strains. The characterization of the AC binder properties serves as direct required input to estimate the Master Curve (Complex Modulus-Reduced Time) of the specified asphalt mixture.

Project 3: *ADOT AC Mixture Stiffness Characterization Database* provides ADOT with a comprehensive database of the dynamic modulus stiffness properties associated with typical ADOT mixtures. The E* database includes the detailed test data, numerically optimized master curves and data required for the Witczak E* predictive model. These properties data are required to implement the pavement design and analysis of the M-E PDG at all analysis levels.

Project 4: *ADOT AC Thermal Fracture Characterization* provides ADOT with a comprehensive database of the thermal fracture properties specifically associated with eleven conventional ADOT mixtures and four asphalt rubber mixes. The database included creep compliance and tensile strength test data at different temperatures. These properties are fundamental material inputs required in the M-E PDG. In addition, energy-until-failure and total fracture energy results were provided.

Project 5: *ADOT AC Mix Permanent Deformation Database* provides ADOT with a repeated-load permanent-strain database collected from repeated load dynamic tests. In addition to this comprehensive database collected from 13 different projects, a model to predict the permanent deformation behavior was developed.

Project 6: *ADOT AC Fatigue Characterization Database* provides ADOT with a comprehensive database of six typical ADOT HMA mixture fracture (fatigue) properties and parameters for use in the implementation of the M-E PDG system. Furthermore, a global fatigue cracking model specific for ADOT HMA mixtures was developed. This model can be used to predict the fatigue life of any ADOT mix with a high degree of precision.

Project 7: *ADOT Implementation of Simple Performance AC Mixture Test* provides ADOT with a comprehensive field validation of the recommended approach for the Simple Performance Test. A database comprising F_n and F_t data, permanent strain at flow, recoverable strain at flow, $\varepsilon_p/\varepsilon_r$ from F_n test, compliance from F_t test, and mixture data related to all F_n and F_t tests was elaborated under this project.

Project 8: *ADOT Unbound Materials Modulus Database* developed a set of typical k_1-k_3 material parameters for a range of typical Arizona base, subbase and subgrade soil conditions used in Arizona highway construction areas. This database was used to calibrate a resilient modulus predictive model for ADOT unbound materials that is capable of estimating changes in modulus as a function of changes in state of stress, moisture and density. This model can be used in pavement response models and mechanistic-empirical design methods and fulfills key requirements of accuracy, computational stability and implementability in existing mechanistic-empirical design methodologies.

Project 9: *ADOT Unbound Materials Permanent Deformation Database and Development of Universal Permanent Strain Model* was directed towards the development of a rational mechanistic constitutive model to predict permanent deformation of the unbound subgrade, subbase and base materials provided by ADOT to implement the new M-E PDG for Arizona conditions under dynamic repeated load repetitions. The model that was developed considers both the permanent as well as the resilient strain, which can be directly calculated from multi-layer elastic pavement response models. The goodness of fit statistics of the developed model as well as the residual analysis showed excellent accuracy and low bias.

Project 10: *Implementing EICM to Arizona Climatic Conditions* provided ADOT with the input environmental parameters needed to define the Arizona climatic conditions for the Enhanced Integrated Climatic Model (EICM) module of the M-E PDG. Default input climatic files for Arizona conditions were developed and typical climatic zones within the state were proposed. Finally, the software was made to either generate climatic input files or to retrieve the default available data when it was presented. A user guide to the software was also compiled.

Project 11: *Development of Design Guide Traffic Files for ADOT* provides a traffic database of the entire Arizona highway network for pavement analysis and design. The database has data on six interstates, 13 US highways and 86 state highways. It will accommodate the current ADOT Geographical Information System (GIS) for mapping purposes and can be used in the implementation of the M-E PDG for Arizona.

A summary of the results and conclusions for each project is presented in the following sections. More complete reports on each project and data are in the appendixes.

Final ADOT Project Reports
ASU Project XCT 9294
Development of Performance Related Specifications

Project # 1

"Development of Work Plan," June 2000

Project # 2

"ADOT Asphalt Cement Binder Characterization Database," December 2000

Project # 3

"ADOT AC Mix Stiffness Characterization Database," March 2005*
Dynamic Modulus (E*) Test and Master Curve- Part I
Dynamic Modulus (E*) Test and Master Curve- Part II
Dynamic Modulus (E*) Test and Master Curve- Part III

*Because of the huge volume of information, this report is divided into 3 parts of data

Project # 4

"ADOT Asphalt Concrete Thermal Fracture Characterization," December 2004
Vol I of IV: Main Report and Appendix A-H
Vol II of IV: Appendix I
Vol III of IV: Appendix I (Cont'd)
Vol IV of IV: Appendix J

Project # 5

"ADOT AC Mixture Permanent Deformation Characterization Permanent Strain Model," April 2004

Project # 6

"ADOT Asphalt Concrete Mixture Fatigue Characterization," December 2003

Project #7

"ADOT AC Mixture Permanent Deformation Database: Simple Performance Test (SPT) Flow Number (Fn) and Flow Time (Ft) Databases," March 2005

Special Note: For additional ADOT AC Mixture Fn and Ft Analysis, the reader is referred to the "Master CD File / Report Listings for NCHRP 9-19 Project Reports". This is contained in Chapter 4, Table 2, pg 15 of NCHRP

547, "Simple Performance Tests: Summary of Recommended Methods and Database", Washington, D.C., 2005

Refer to Major Area – PDF File No. for the following reports:

<u>NCHRP 9-19 PDF No 13-E</u>
"Superpave Support and Performance Models Management: Use of the Flow Number (Fn) and Flow Time (Ft) Test as a Simple Performance Test for Asphalt Pavement Systems (AC Permanent Deformation)"

<u>NCHRP 9-19 PDF No 13-G</u>
"Superpave Support and performance Models Management Database- Flow Number (Fn) and Flow Time (Ft), AC Mixture Simple Performance Tests

<u>Project # 8</u>

"ADOT Unbound Materials Characterization Database and Analysis of Typical ADOT Base and Subbase Materials," July 2003
Vol I of II (Main text report)
Vol II of II (All report Appendices)

<u>Project # 9</u>

"ADOT Unbound Materials Permanent Deformation Database and Development of Universal Permanent Strain Model," March 2006

<u>Project # 10</u>

"Implementation of the EICM to Arizona Climatic Conditions," December 2000

<u>Project # 11</u>

"Development of Design Guide Traffic Files for ADOT," July 2003
Vol I of II (Main report to Appendix 5)
Vol II of II (Appendix 6 to Appendix 18)

Project 1: Development of Work Plan

Objective
The objective of this project was to present an overall research program to develop performance related specifications for asphalt pavements Arizona.

Program Goals
The Project 1 report detailed a five-year research program, initiated in July 1999, having as its goal the implementation of a methodology for Performance Related Specifications for asphalt pavements in Arizona. There were several very important and allied goals for the proposal. They were to:

1. Initiate and develop a fully coordinated and integrated pavement research program consisting of ASU and ADOT personnel to focus on the enhancement of technological and economic aspects related to pavement design, performance and construction in the state of Arizona.

2. Integrate into the Arizona research program the results of the most recent national research work being conducted on mechanistic pavement performance modeling. This would insure that the most cost efficient and technologically state-of-the-art research was immediately implemented and utilized in Arizona. This advanced pavement design and analysis system would be the Mechanistic-Empirical Pavement Design Guide (M-E PDG).

3. Develop an enhanced asphalt mixture design system that will be based upon the most recent advances formulated by the new U.S. Superpave system. In particular, the proposed research program described in this proposal would also utilize the most recent findings of the Superpave Models study conducted under NCHRP Project 9-19. This should also result in ADOT being at the forefront of U.S. asphalt pavement technology and provide ADOT with the most advanced technology for asphalt mix design and field quality assurance/quality control purposes, as well as the most cost effective construction technology available in the country.

General Overview
Of paramount importance was the simultaneous development of typical design input parameters for Arizona conditions. It would then be possible to utilize the M-E PDG to assess how well (or poorly) the predicted performance of Arizona pavements agrees with nationally calibrated models. In all likelihood, minor modifications and enhancements to the material models, distress predictions and general methodology of the national (US) M-E PDG would be required. This would be accomplished through a calibration-validation effort of the national M-E PDG to insure that it was truly accurate for design conditions (traffic, materials of construction, environment) in Arizona. Once this Arizona-calibrated design model was produced, development of a true performance-based set of specifications for Arizona asphalt construction could be developed and implemented.

Table 1 is a summary of the research program contained in the work plan. Also noted is the fact that the overall program was subdivided into three major work phases. The Phase I effort was development of the work plan, described in this chapter. Phase II was termed *Characterization of the ADOT Design Input Parameters* because the projects (No. 2 to No. 11) are related to the development of all of the material parameters, traffic and environmental inputs required as input for the M-E PDG methodology. These projects were considered mandatory if a truly ADOT calibrated design approach were to be developed. The projects in Phase III relate to the development of an implementable Arizona Design Guide, in order that an accurate PRS system could be developed. Phase III consisted of projects 12 to 14.

Table 1. Summary of Research Projects

Phase	Project No	Description	Anticipated Period	No of Months
I - Work Plan Development				
	1	*Develop Work Plan for Pvt Research Program*	*1 July 99 - 30 June 00*	*12*
II - Characterize ADOT Input Parameters				
(AC Mix Properties)				
	2	*ADOT AC Binder Characterization Database*	*1 July 99 - 31 Dec 00*	*18*
	3	*ADOT AC Mix Stiffness Database*	*1 Jan 00 - 31 Dec 01*	*24*
	4	*ADOT AC Thermal Fracture Characterization*	*1 Oct 00 - 31 Dec 01*	*15*
	5	*ADOT AC Mixture Perm Deformation Database*	*1 Jan 00 - 31 Dec 01*	*24*
	6	*ADOT AC Fatigue Characterization Database*	*1 Apr 00 - 31 Dec 01*	*21*
	7	*ADOT Implementation of Simple Performance Test*	*1 Apr 00 - 31 Dec 01*	*21*
(Unbound Materials)				
	8	*ADOT Unbound Materials Modulus Database*	*1 Apr 00 - 31 Dec 01*	*21*
	9	*ADOT Unbound Materials Perm Def Database*	*1 Apr 00 - 31 Dec 01*	*21*
(Environmental)				
	10	*Implement EICM to Arizona Climatic Conditions*	*1 Jan 00 - 31 Dec 00*	*12*
(Traffic)				
	11	*Develop Design Guide Traffic Files for ADOT*	*1 Apr 00 - 31 Dec 01*	*21*
III - Implementation of System Methodology				
	12	*ADOT Performance Prediction of Design Guide*	*1 Jan 02 - 30 Jun 03*	*18*
	13	*Calibration - Validation of Design Guide for ADOT*	*1 Apr 02 - 30 Sept 03*	*18*
	14	*Develop ADOT Performance Related Specifications*	*1 Jan 03 - 30 Jun 04*	*18*

AC/MIX PROPERTIES

Project 2: ADOT AC Binder Characterization Database

Project Objective

The objective of the ADOT AC Binder Characterization Database Project was to develop Superpave-American Association of State Highway and Transportation Officials (AASHTO) properties for typical AC binders used in ADOT construction projects.

Experimental Plan

Six AC binders commonly used in HMA pavements within Arizona were evaluated. All of these binders were selected and supplied by ADOT. These binders are listed in Table 2.

Table 2. List of AC Binders Tested

Manufacturer	Performance Grade (Referenced by supplier)	Abbreviation
Paramount	58-22	P1
Paramount	64-16	P2
Chevron	64-22	C1
Chevron	76-16	C2
Navajo Western	70-10	N1
Navajo Western	76-16	N2

The following binder tests were performed:

1. Penetration value at 15°C and 25°C with 100 gm load for five seconds using standard Penetrometer (AASHTO T 49-03).
2. Softening point using the Ring and Ball apparatus (AASHTO T 53-96, 2000).
3. Absolute viscosity at 60°C using the capillary-type vacuum viscometer (AASHTO T 202-03).
4. Kinematic viscosity at 135°C using the Kinematic Viscometer (AASHTO T 201-03).
5. Rotational viscosity at 60°C, 80°C, 100°C, 121.1°C, 135°C and 176.7°C using the Brookfield Viscometer (AASHTO T 316-02).
6. Low temperature flexural creep stiffness parameters: S (Stiffness measured in Mega Paskals and m (slope of Stiffness per second)- at three temperatures in 0°C to -40°C range; one above the low temperature specification limit and two below that limit, by testing the specimen for 240 seconds under a creep load of 980 ± 50 mN (millinewtons) using the Bending Beam Rheometer (BBR) (AASHTO T 313-03).
7. Complex shear modulus (G*) and phase angle (δ) at 15°C, 25°C, 35°C, 45°C, 60°C, 70°C, 80°C, 95°C, 105°C and 115°C under the oscillatory loading frequencies of 1, 10 and 100 radians per second using the Dynamic Shear Rheometer (DSR) (AASHTO T 315-02).
8. Low temperature ultimate tensile strain in the temperature range of 0°C to –36°C using the Direct Tension Tester (DTT) (AASHTO T 314-02).
9. Accelerated in-service aging of asphalt binder using the Pressure Aging Vessel (PAV) at both 100°C and 110°C (AASHTO R 28-02)

The aforementioned tests were conducted at four aging conditions: a) original or tank condition; b) construction phase aging of asphalt binder using the Rolling Thin Film Oven (RTFO) according to AASHTO T 240-03; and c) accelerated in-service aging of asphalt binder using the Pressure Aging Vessel (PAV) at both 100°C and d) accelerated in-service aging of asphalt binder using the PAV at 110°C, conducted according to AASHTO R 28-02. At the time of this report completion, the latest AASHTO test specification year was cited.

Binder test data obtained from the Penetration, Ring and Ball, Absolute Viscosity and Kinematic Viscosity tests were converted to viscosity in centipoises. These data, along with the Brookfield viscosity data, were plotted using the ASTM A_i-VTS_i equation to obtain the regression parameters "A" and "VTS".

The detailed test results are included in the appendixes. The results showed consistent trend in that the binders with higher PG grade and/or more aging showed characteristics of stiffer binder (e.g., lower penetration, and higher softening point, viscosity and stiffness). The Direct Tension test result showed that all but the PAV110-aged P2 binder had failure strains greater than the minimum value of 1% as specified in the P G graded asphalt binder specifications. The DSR test data of the N2 binder showed a modified binder's phase angle behavior as its phase angle did not consistently increase towards 90 degrees as the temperature increased. The rest of the binders exhibited phase angle behavior typical of conventional asphalt.

Analysis

Conformance to Permanent Deformation and Fatigue Cracking Specifications

Figures 1 and 2 show comparisons of ADOT binders at different aging conditions for the Superpave rutting and fatigue cracking characteristics, respectively. Only the P2 binder failed to satisfy the criteria for limiting fatigue cracking at both PAV100 and PAV110. The BBR stiffness and m-values of all the binders were checked at respective reference temperatures (Table 3). At both PAV100 and PAV110, the C2 binder failed to achieve the minimum m-value of 0.300. Since the Direct Tension test results confirmed that as this binder passed the Superpave criteria for direct tension, the discrepancies found in the BBR test might be ignored.

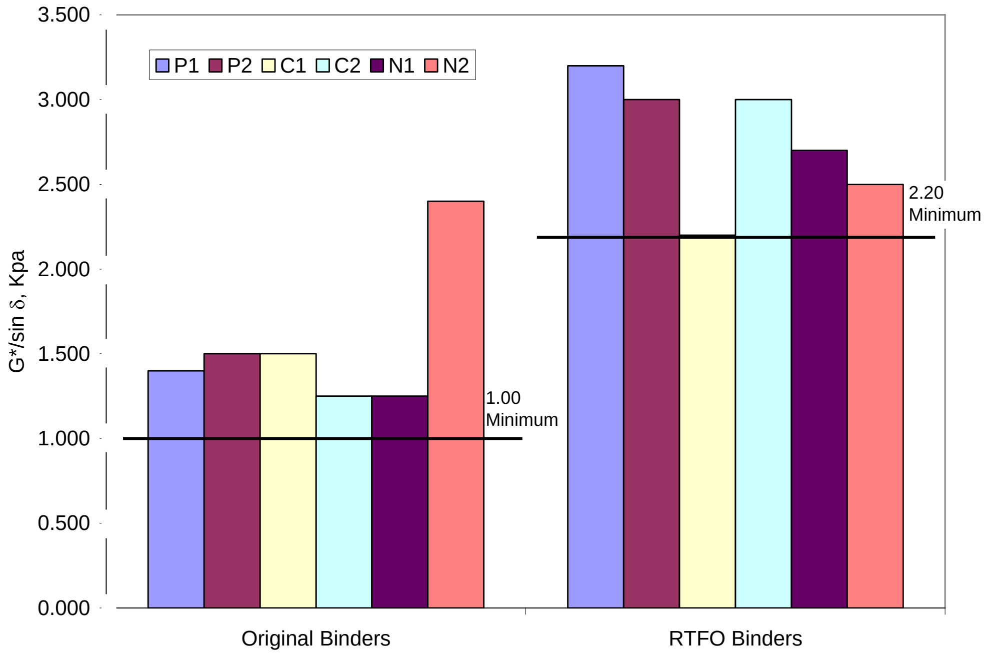

Figure 1. Comparison of Rutting Characteristics of ADOT Binders

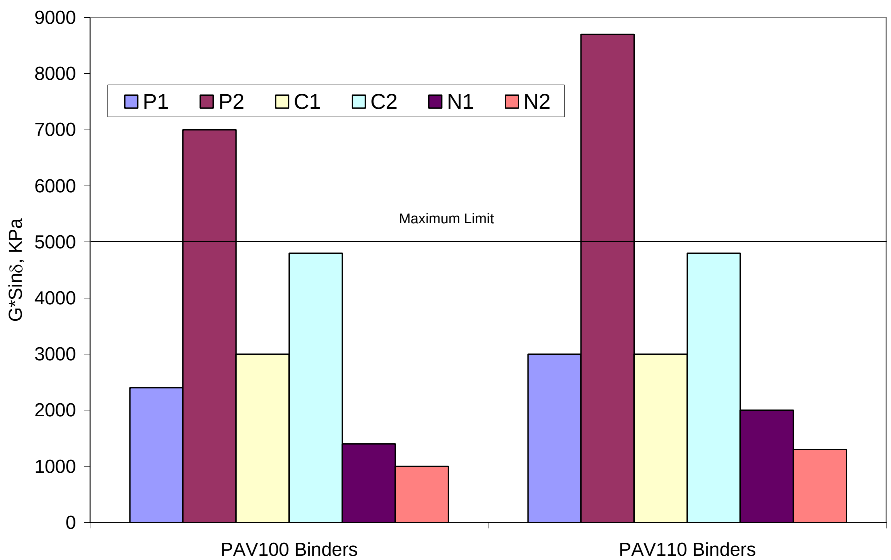

Figure 2. Comparison of Fatigue Cracking Characteristics of ADOT Binders

Table 3. BBR Stiffness and m-Value at Test Temperatures

Binder	Stiffness and m-values at PAV100 and PAV110				Remark
	Temp. (°C)	Age	Stiffness (MPa)	m-Value	
P1	-12	PAV100	87.5	0.399	Pass
	-12	PAV110	81.0	0.398	Pass
P2	-6	PAV100	272.5	0.346	Pass
	-6	PAV110	282.0	0.332	Pass
C1	-12	PAV100	112.0	0.307	Pass
	-12	PAV110	124.5	0.303	Pass
C2	-6	PAV100	86.2	**0.299**	**Fail**
	-6	PAV110	93.0	**0.294**	**Fail**
N1	0	PAV100	92.2	0.349	Pass
	0	PAV110	111.5	0.341	Pass
N2	-6	PAV100	95.4	0.335	Pass
	-6	PAV110	102.0	0.323	Pass

Conformance to Penetration, Viscosity and Performance Grades

The binders were evaluated for grade-conformance to Penetration, Viscosity and Performance grades. The summary of this evaluation is shown in Table 4.

Table 4. Actual Binder Grades

Binder	Abbr.	Penetration Grade	Viscosity Grade	Performance Grade
Paramount 58-22	P1	120-150	AC-10	58-28
Paramount 64-16	P2	40-50	AC-20	58-16
Chevron 64-22	C1	40-50	AC-30	64-22
Chevron 76-16	C2	<40-50	> AC-40	76-16
Navajo 70-10	N1	<40-50	AC-40	70-10
Navajo 76-16	N2	40-50	-	76-22

Consistency-Temperature Relationships

The consistency-temperature relationships of all original binders are graphically shown in Figure 3. It is observed that the N2 binder is the least temperature susceptible, while the C1 and N1 binders are the most temperature susceptible. For binders tested at original condition, the modified asphalt binder (N2) exhibited the lowest (best) temperature susceptibility. It proved to be even better when compared with another binder of the same Performance Grade (unmodified C2). The A and VTS values obtained from the regression analyses can be found in the final report.

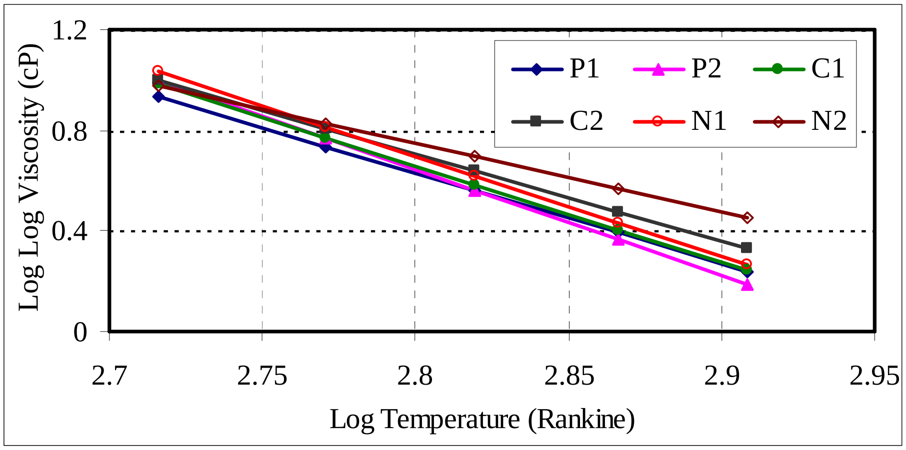

Figure 3. Consistency-Temperature Relationship of ADOT Original Binders

Comparison of A and VTS Values to Typical Values

The M-E PDG includes recommended values of A and VTS for RTFO aged binders of different grades. The A and VTS values of the P2 and N1 binder were found to be slightly higher than the recommended values.

Influence of Aging on Binder Properties

Based on the test data, the binders showed characteristics of stiffer binders (e.g., lower penetration, and higher softening point, viscosity and stiffness) as they were aged more. Data showed that for the original conditions, the P1, N1 and N2 binders exhibited the best low temperature characteristics. On the other hand, C2 failed to achieve the minimum RTFO+PAV m-value of 0.300. While comparing this unmodified C2 binder with the same graded modified N2 binder, it was observed that the stiffness values at -6^{o}C were very close, but the m-value was much better for the case of the modified binder. This result suggested that improvement of low temperature properties might be achieved by polymer modification of harder asphalt binders.

Comparison between PAV100 and PAV110 Aging Characteristics

The comparative analysis of the BBR stiffness and m-value at PAV temperatures of 100^{o}C and 110^{o}C shows some variations between the PAV100 and PAV110 aging characteristics for the P1 and C1 at high temperatures and in the case of P2 and C2 at lower temperatures. No variation was observed in the cases of N1 and N2. An analysis of variance (ANOVA) indicated that there is a statistically significant difference between PAV100 and PAV110 characteristics for the softer binders (P1, P2 and C1), whereas no statistically significant variation was found for the stiffer binders.

Study of ADOT Binders Using Predictive Models for G and δ*

Using the A and VTS values obtained from the ASTM Ai-VTSi equation, viscosity values for 15°C, 25°C, 35°C, 45°C, 60°C, 70°C, 80°C, 95°C, 105°C and 115°C at different aging conditions were calculated, and viscosity values were predicted based on the G* predictive model developed by Bonaquist, Pellinen and Witczak (1), which is used in the M-E PDG. The model is as follows:

$$\eta = \left(\frac{|G^*|}{\omega}\right)\left(\frac{1}{\sin\delta}\right)^{a_o + a_{1\omega} + a_2\omega^2} \quad (1)$$

Where: η = viscosity from ASTM viscosity-temperature equation; |G*| = measured shear modulus (Pa); δ = measured phase angle (degrees); ω = angular frequency used to measure G* and δ; a_o, a_1 and a_2 = fitting parameter for all types of binders (i.e., 3.639216, 0.131373 and -0.000901, respectively).

The calculated and predicted viscosities are compared in Figure 4. The results suggest that the predictive equation shown above can reasonably estimate the viscosity of ADOT binders.

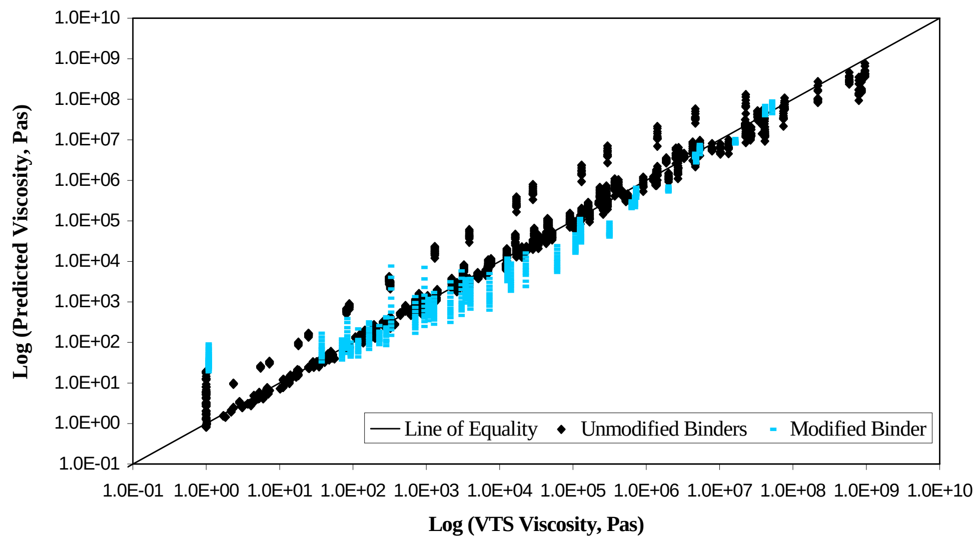

Figure 4. Predicted vs. Calculated Viscosity

Ranking of ADOT Binders

The six ADOT binders were ranked according to their <u>intermediate to high temperature performance</u> against permanent deformation and fatigue cracking. The binder performance against permanent deformation was evaluated at 80°C and 45°C. Similarly, performance against fatigue cracking was evaluated at 35°C and 25°C. G*/sinδ and

G*sinδ values were used to rank the binders. The ranking details used to obtain the final combined ranking shown in Table 5 are clearly amplified in pg. 71~74 of Project.2 "ADOT Asphalt Cement Binder Characterization Database" (in the appendixes).

Table 5. Final Ranking of Binders

Rank	Binder
1	N2
2	C2
3	C1
4	P1
5	N1
6	P2

Conclusions
The P2 binder had the Performance Grade of a 58-16 compared to the ADOT noted Performance Grade of a 64-16. The P1 (ADOT noted PG 58-22) and N2 (ADOT noted PG 76-16) binders, however, had one-step lower temperature grades of -28 and -22, respectively.

The rotational viscosity data (of Brookfield tests) indicated that at the lower temperature range (60^{o}C to 80^{o}C), the stiffer binders showed sensitivity to the shearing rate. From the point of view of temperature susceptibility, the PAV110 aged binders showed slightly better performance than the same set of binders aged at PAV100. The viscosity-temperature susceptibility behavior of the binders indicated that N2 exhibited the lowest (the best) temperature susceptibility, whereas, P1 exhibited the highest (the worst) temperature susceptibility.

The predictive model for binder complex shear modulus (G*), which was established by Bonaquist et al (1) and is being used in the M-E PDG, worked reasonably well for the binders tested in this study. Finally, the six test binders were ranked according to their intermediate to high temperature performance against permanent deformation and fatigue cracking. They ranked as follows: (1) N2, (2) C2, (3) C1, (4) P1, (5) N1, and (6) P2.

Project 3: ADOT AC Mix Stiffness Characterization Database

Project Objective

The goal of the ADOT AC Mixture Stiffness Characterization Database Project was to develop a comprehensive database of the dynamic modulus (E*) stiffness properties of typical ADOT mixtures.

Significance and Use

The E* stiffness modulus of the asphalt concrete is the fundamental material input parameter required at all three analysis levels of the M-E PDG. E* values at all temperatures and time rates of load are determined from a master curve constructed at a reference temperature generally taken as 70ºF (21ºC). The laboratory E* test data is the required input for Level 1 analysis, where the master curve is developed using a numerical optimization to shift the laboratory mix E* test data. Prior to shifting the mixing data, the relationship between binder viscosity and temperature is established. Typical ADOT AC binders were characterized under Project 2, presented above, to obtain a database for this purpose. The master curve for the Level 2 analysis is developed using the Witczak E* predictive model from specific laboratory test data. The Level 3 analysis does not require laboratory test data for the AC binder but requires mixture properties to feed the Witczak E* predictive model.

The E* database includes the detail test data, numerically optimized master curves (with all required fitting parameters) and data required for the Witczak E* predictive model. Thus, the database can be used for all levels of analysis of the M-E PDG.

Mixtures Used throughout the Testing Program

The testing program included complete E* characterization of 11 conventional mixtures (lab blended) using five different aggregates, as follows:

1. Salt River Base mix: Three conventional lab blended mixtures (PG 64-22, 70-10 and 76-16) using the Salt River Base Aggregates.
2. Salt River ¾" mix: Three conventional lab blended mixtures (PG 64-22, 70-10 and 76-16) using the Salt River ¾" Aggregates.
3. Bidahouchi Base mix: Two conventional lab blended mixtures (PG 58-28 and 64-22) using the Bidahouchi Base Aggregates.
4. Bidahouchi ¾" mix: Two conventional lab blended mixtures (PG 58-28 and 64-22) using the Bidahouchi ¾" Aggregates.
5. Two Guns-Dennison mix: One conventional lab blended Superpave mixture.

In addition, the following 23 mixtures were included in the master database:

6. ADOT US-60: Two conventional plant mixtures (1^{st} and 2^{nd} lift at Deer Valley Road - 203rd Ave.).
7. ADOT I-10: Six conventional plant mixtures (SPS-9 04B900: Oglesby-Perryville Road Project).
8. Flagstaff, Perryville and Kingman sites: Six conventional mixtures (field cores and plant mixtures).
9. ADOT I-40 site: Two asphalt rubber plant mixtures (PG 58-22 AR gap and open graded mix).

10. ADOT I-17 site: Two asphalt rubber plant mixtures (PG 58-22 AR gap and PG 64-16 AR gap graded mix) at three air voids levels.
11. ADOT I-17 site: Aging characteristics of two gap graded asphalt rubber plant mixtures (PG 58-22 AR gap and PG 64-16 AR gap graded mix) at two oven aging stages; 5 days and 14 days.
12. Two Guns-Dennison plant mixtures: One conventional plant mix (PG 64-22), one gap graded asphalt rubber mix (AR PG 58-22) and one open graded asphalt rubber mix (AR PG 58-22).

Summary of Test Method

All E* tests were carried out according to the "Standard Test Method for Dynamic Modulus of Asphalt Concrete Mixtures" that was developed at ASU and eventually adopted as AASHTO TP 62-03. Before compaction, the laboratory blended AC mixtures were short-term aged in the oven for four hours at 275ºF (135ºC), according to AASHTO test method AASHTO PP2 – "Standard Practice for Short and Long Term Aging of Hot Mix Asphalt." Any lab-blended or plant-obtained mixture was compacted in a Servopac gyratory compactor to 6-in diameter by 6.7-in high. All test specimens were sawed and cored to obtain the final 4-in diameter by 6-in high E* test specimens. Before the E* testing, AASHTO T166-93 was followed to measure the bulk specific gravity and water absorption of the specimens. All the lab-blended specimens were prepared to have about 7% air voids ± 0.5%.

For each mix, generally two or three replicates were prepared for E* testing. For each specimen, E* tests were conducted at 14°F, 40°F, 7°F 0, 10°F 0 and 130°F for 25 Hz, 10 Hz, 5 Hz, 1 Hz, 0.5 Hz and 0.1Hz loading frequencies. A 60-second rest period was used between each frequency to allow specimen recovery before applying the new loading at a lower frequency. The E* tests were done using a controlled stress mode, which produced strains smaller than 200 micro-strain. Table 6 presents the E* test conditions.

Table 6 Test Conditions of the Dynamic Modulus (E*) Test

Test Temp. (°F)	Freq. (Hz)	Cycles	Rest Period (Sec)	Cycles to Compute E*
14, 40, 70, 100, 130 (Unless otherwise specified)	25	200	-	196 to 200
	10	100	60	196 to 200
	5	50	60	96 to 100
	1	20	60	16 to 20
	0.5	15	60	11 to 15
	0.1	15	60	11 to 15

The dynamic Modulus (E*) Test was performed against a range of temperatures to determine if the material would provide a linear response. The dynamic stress levels were 10 psi to 100 psi for colder temperatures (14°F to 70°F) and 2 psi to 10 psi for higher temperatures (100°F to 130°F). All E* tests were conducted in a temperature-controlled chamber capable of holding temperatures from 3.2°F to 140°F (–16°C to 60°C).

The axial deformations of the specimens were measured through two spring-loaded Linear Variable Differential Transducers (LVDTs) placed vertically on diametrically opposite sides of the specimen. Parallel brass studs were used to secure the LVDTs in place. Two pairs of studs were glued on the two opposite cylindrical surfaces of a specimen, each stud in a pair, being 100-mm (4 in) apart and located at approximately the same distance from the top and bottom of the specimen. Figure 5 shows the setup for the E* testing. To eliminate the possibility of having shear stresses on the specimen ends during testing, pairs of rubber membranes, with vacuum grease within the pairs, were placed on the top and bottom of each specimen.

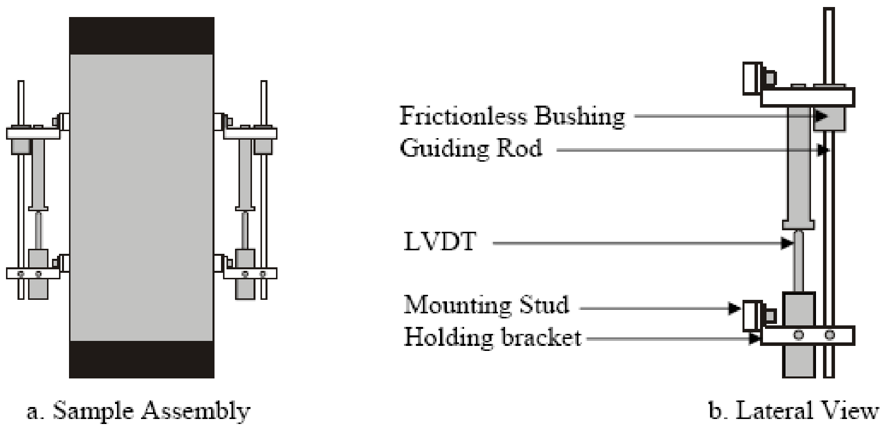

Figure 5 Sample Assembly for E* Test

Summary and Results

Table 7 lists all the mixtures tested and included in the database. The master E* database includes:

1. E* Database from Project 3 mixtures, which is comprised of Salt River (Base & ¾”) , Bidahouchi (Base and ¾”), as well as US-60, and Two Guns..
2. E* Database from the “Asphalt Rubber Demonstration Project” (ADOT I-40 Buffalo Range Section, MP 220).
3. E* Database (AR Tasks 2 and 3) from the ASU-ADOT project titled *Performance Evaluation of Arizona Asphalt Rubber Mixtures Using Advanced Dynamic Material Characterization Tests* (Arizona Asphalt Rubber Mixtures in the ADOT I-17 McDowell Frontage Road Section MP 200).
4. E* Database from Task C of NCHRP 9-19 project titled *Superpave Support and Performance Models Management*.
5. E* Database from NCHRP 9-23 project titled *Environmental Effects in Pavement Mix and Structural Design Systems*.
6. E* Database from lime modified asphaltic mixtures of the National Lime Association – Arizona State University (NLA-ASU) research project titled *Development of an E* Master Curve Database for Lime Modified Asphaltic Mixtures*.
7. E* Database from the 2002 and 2003 phases of the *Alberta Asphalt Rubber* project.

Table 7 AC Mix Stiffness Database

Project	Task	Site ID	Sec/ Cell/Lane	Mix ID	Mix Type	Aging	Temp (F)	Va %	Rep	Testing Date
ADOT-ASU (Research Project) Project #3	Mix E* Characterization	ADOT	Salt River Base	Chevron PG 64-22	Lab Blend	4 hrs STOA	14-130	7	3	08/01
				Navajo PG 70-10	Lab Blend	4 hrs STOA	14-130	7	3	08/01
				Chevron PG 76-16	Lab Blend	4 hrs STOA	14-130	7	3	08/01
			Salt River 3/4"	Chevron PG 64-22	Lab Blend	4 hrs STOA	14-130	7	3	11/03
				Navajo PG 70-10	Lab Blend	4 hrs STOA	14-130	7	3	11/03
				Chevron PG 76-16	Lab Blend	4 hrs STOA	14-130	7	3	11/03
			Bidahouchi Base	Paramount PG 58-28	Lab Blend	4 hrs STOA	14-130	7	2	12/03
				Chevron PG 64-22	Lab Blend	4 hrs STOA	14-130	7	2	12/03
			Bidahouchi 3/4"	Paramount PG 58-28	Lab Blend	4 hrs STOA	14-130	7	2	12/03
				Chevron PG 64-22	Lab Blend	4 hrs STOA	14-130	7	2	12/03
			Two Guns	Chevron PG 64-22	Lab Blend	4 hrs STOA	14-130	4.6	2	10/03
			US 60	First lift (bottom)	Plant Mix	Plant	14-130	7.2	2	11/03
				Second lift (top)	Plant Mix	Plant	14-130	6.2	2	11/03
NCHRP 9-19 (Task C)	Subtask C5 (Validation of SPT)	MnRoad	16	AC 20 (PG 64-22)	Lab Blend	4 hrs STOA	14-130	8.2	2	06/99-11/99
			17	AC 20 (PG 64-22)	Lab Blend	4 hrs STOA	14-130	7.7	2	06/99-11/99
			18	AC 20 (PG 64-22)	Lab Blend	4 hrs STOA	14-130	5.6	2	06/99-11/99
			20	Pen 120/150 (PG 58-28)	Lab Blend	4 hrs STOA	14-130	6.3	2	06/99-11/99
			22	Pen 120/150 (PG 58-28)	Lab Blend	4 hrs STOA	14-130	6.5	2	06/99-11/99
NCHRP 9-19 (Task C)	Subtask C5 (Validation of SPT)	MnRoad	1	Pen 120/150 (PG 58-28)	Plant Mix	Plant	14-130	6.31	2	03/02-04/02
			3	Pen 120/150 (PG 58-28)	Plant Mix	Plant	14-130	6.7	2	03/02-04/02
			4	Pen 120/150 (PG 58-28)	Plant Mix	Plant	14-130	6.7	2	03/02-04/02
			14	Pen 120/150 (PG 58-28)	Plant Mix	Plant	14-130	5.9	2	03/02-04/02
			15	AC 20 (PG 64-22)	Plant Mix	Plant	14-130	7.13	2	03/02-04/02
			19	AC 20 (PG 64-22)	Plant Mix	Plant	14-130	6.52	2	03/02-04/02
			21	Pen 120/150 (PG 58-28)	Plant Mix	Plant	14-130	5.14	2	03/02-04/02

Project	Task	Site ID	Sec/ Cell/Lane	Mix ID	Mix Type	Aging	Temp (F)	Va %	Rep	Testing Date
NCHRP 9-19 (Task C)	Subtask C5 (Validation of SPT)	NCAT	E06	Surface	Plant Mix	Plant	14-130	7.1	2	04/03-05/03
			N02	Surface	Plant Mix	Plant	14-130	5.3	2	04/03-05/03
			N03	Surface	Plant Mix	Plant	14-130	5.9	2	04/03-05/03
			N05	Surface	Plant Mix	Plant	14-130	6.2	2	04/03-05/03
			N07	Surface	Plant Mix	Plant	14-130	6.1	2	04/03-05/03
			N11	Lower	Plant Mix	Plant	14-130	6.9	2	04/03-05/03
			N12	Upper	Plant Mix	Plant	14-130	5.4	2	04/03-05/03
			N13	Upper	Plant Mix	Plant	14-130	8	2	04/03-05/03
			S02	Lower	Plant Mix	Plant	14-130	6.2	2	04/03-05/03
			S12	Surface	Plant Mix	Plant	14-130	6.1	2	04/03-05/03
			S13	Surface	Plant Mix	Plant	14-130	6.6	2	04/03-05/03
NCHRP 9-19 (Task C)	Subtask C5 (Validation of SPT)	Indiana	A901	Surface	Plant Mix	Plant	14-130	7.28	3	09/02
			A901	Intermediate	Plant Mix	Plant	14-130	5.72	3	09/02
			A902	Surface	Plant Mix	Plant	14-130	4.79	3	09/02
			A902	Intermediate	Plant Mix	Plant	14-130	3.83	3	09/02
			A903	Surface	Plant Mix	Plant	14-130	7.47	3	09/02
			A903	Intermediate	Plant Mix	Plant	14-130	4.85	3	09/02
			A959	Surface	Plant Mix	Plant	14-130	7.65	3	09/02
			A959	Intermediate	Plant Mix	Plant	14-130	4.04	3	09/02
			A960	Surface	Plant Mix	Plant	14-130	8.03	3	09/02
			A960	Intermediate	Plant Mix	Plant	14-130	8.35	3	09/02
			A961	Surface	Plant Mix	Plant	14-130	9.3	3	09/02
			A961	Intermediate	Plant Mix	Plant	14-130	6.59	3	09/02
NCHRP 9-19 (Task C)	Subtask C5 (Validation of SPT)	Nevada I-80	Top	SPAC-20P	Plant Mix	Plant	14-130	5.66	2	06/02-08/02
			Bottom	SPAC-20P	Plant Mix	Plant	14-130	2.03	2	06/02-08/02
			Top	SPPG64-22	Plant Mix	Plant	14-130	5.79	2	06/02-08/02
			Bottom	SPPG64-22	Plant Mix	Plant	14-130	2.02	2	06/02-08/02
			Top	NVPG64-22	Plant Mix	Plant	14-130	6.24	2	06/02-08/02
			Bottom	NVPG64-22	Plant Mix	Plant	14-130	5.98	2	06/02-08/02
			Top	NVAC-20P	Plant Mix	Plant	14-130	6.23	2	06/02-08/02
			Bottom	NVAC-20P	Plant Mix	Plant	14-130	6.51	2	06/02-08/02

Project	Task	Site ID	Sec/ Cell/Lane	Mix ID	Mix Type	Aging	Temp (F)	Va %	Rep	Testing Date
NCHRP 9-19 (Task C)	Subtask C5 (Validation of SPT)	WesTrack	WST-C2	Bottom	Lab Blend	4 hrs STOA	14-130	9.3	2	11/00-12/00
			WST-C5	Bottom	Lab Blend	4 hrs STOA	14-130	7	2	11/00-12/00
			WST-C6	Bottom	Lab Blend	4 hrs STOA	14-130	11.3	2	11/00-12/00
			WST-C24	Bottom	Lab Blend	4 hrs STOA	14-130	7.5	2	11/00-12/00
			WST-R2	Top	Lab Blend	4 hrs STOA	14-130	10.4	2	11/00-12/00
			WST-R4	Top	Lab Blend	4 hrs STOA	14-130	6.6	2	11/00-12/00
			WST-R7	Top	Lab Blend	4 hrs STOA	14-130	6.9	2	11/00-12/00
			WST-R15	Top	Lab Blend	4 hrs STOA	14-130	8.7	2	11/00-12/00
			WST-R23	Top	Lab Blend	4 hrs STOA	14-130	4.9	2	11/00-12/00
			WST-R24	Top	Lab Blend	4 hrs STOA	14-130	7.2	2	11/00-12/00
NCHRP 9-19 (Task C)	Subtask C5 (Validation of SPT)	WesTrack	W-01	Top	Plant Mix	Plant	14-130	8.75	2	02/03-03/03
			W-03	Top	Plant Mix	Plant	14-130	12.43	2	02/03-03/03
			W-04	Top	Plant Mix	Plant	14-130	6.55	2	02/03-03/03
			W-05	Top	Plant Mix	Plant	14-130	8.1	2	02/03-03/03
			W-06	Top	Plant Mix	Plant	14-130	10.78	2	02/03-03/03
			W-07	Top	Plant Mix	Plant	14-130	6.87	2	02/03-03/03
			W-08	Top	Plant Mix	Plant	14-130	8.5	2	02/03-03/03
			W-09	Top	Plant Mix	Plant	14-130	3.91	2	02/03-03/03
			W-10	Top	Plant Mix	Plant	14-130	11.79	2	02/03-03/03
			W-11	Top	Plant Mix	Plant	14-130	7.85	2	02/03-03/03
			W-12	Top	Plant Mix	Plant	14-130	4.55	2	02/03-03/03
			W-13	Top	Plant Mix	Plant	14-130	5.91	2	02/03-03/03
			W-14	Top	Plant Mix	Plant	14-130	9	2	02/03-03/03
			W-15	Top	Plant Mix	Plant	14-130	8.69	2	02/03-03/03
			W-16	Top	Plant Mix	Plant	14-130	12.22	2	02/03-03/03
			W-17	Top	Plant Mix	Plant	14-130	11.04	2	02/03-03/03
			W-18	Top	Plant Mix	Plant	14-130	4.33	2	02/03-03/03
			W-19	Top	Plant Mix	Plant	14-130	7.16	2	02/03-03/03
			W-20	Top	Plant Mix	Plant	14-130	10.91	2	02/03-03/03
			W-21	Top	Plant Mix	Plant	14-130	4.18	2	02/03-03/03
			W-23	Top	Plant Mix	Plant	14-130	4.92	2	02/03-03/03
			W-24	Top	Plant Mix	Plant	14-130	7.2	2	02/03-03/03

Project	Task	Site ID	Sec/ Cell/Lane	Mix ID	Mix Type	Aging	Temp (F)	Va %	Rep	Testing Date
NCHRP 9-19 (Task C)	Subtask C5 (Validation of SPT)	FHWA-ALF	5 (Site 2)	AC-10	Lab Blend	4 hrs STOA	14-130	8.6	2	01/00-02/00
			7 (Site 2)	Strylf	Lab Blend	4 hrs STOA	14-130	11.9	2	01/00-02/00
			8 (Site 2)	Novoplant	Lab Blend	4 hrs STOA	14-130	11.9	2	01/00-02/00
			9 (Site 2)	AC-5	Lab Blend	4 hrs STOA	14-130	7.7	2	01/00-02/00
			10 (Site 2)	AC-20	Lab Blend	4 hrs STOA	14-130	9.3	2	01/00-02/00
			11 (Site 2)	AC-5	Lab Blend	4 hrs STOA	14-130	6	2	01/00-02/00
			12 (Site 1)	AC-20	Lab Blend	4 hrs STOA	14-130	7.4	2	01/00-02/00
			1 (Site 1)	AC-5	Lab Blend	4 hrs STOA	14-130	6.1	2	01/00-02/00
			2 (Site 1)	AC-20	Lab Blend	4 hrs STOA	14-130	6.5	2	01/00-02/00
			3 (Site 1)	AC-5	Lab Blend	4 hrs STOA	14-130	7.7	2	01/00-02/00
			4 (Site 1)	AC-20	Lab Blend	4 hrs STOA	14-130	99.7	2	01/00-02/00
NCHRP 9-19 (Task C)	Subtask C5 (Validation of SPT)	FHWA-ALF	5 (Site 2)	AC-10	Field Core	Field	14-130	8.51	2	01/03-02/03
			7 (Site 2)	Strylf	Field Core	Field	14-130	12.12	2	01/03-02/03
			8 (Site 1)	Novoplant	Field Core	Field	14-130	11.66	2	01/03-02/03
			9 (Site 2)	AC-5	Field Core	Field	14-130	7.56	2	01/03-02/03
			10 (Site 1 & 2)	AC-20	Field Core	Field	14-130	8.88	2	01/03-02/03
			11 (Site 1 & 2)	AC-5	Field Core	Field	14-130	6.11	2	01/03-02/03
			12 (Site 1)	AC-20	Field Core	Field	14-130	7.4	2	01/03-02/03
ASU-ADOT (+ NCHRP 9-19)	Mix E* Characterization (Validation of SPT)	ADOT	I-10	SMA Polymer w/o ACFC	Plant Mix	Plant	14-130	6.07	3	05/03-06/03
				SMA Cellulose	Plant Mix	Plant	14-130	6.77	3	05/03-06/03
				SP Level 1 (4.3% AC-40)	Plant Mix	Plant	14-130	6.80	3	05/03-06/03
				SP Level III (3.8% AC-40)	Plant Mix	Plant	14-130	7.00	3	05/03-06/03
				SP Level III (4% PG 76-10)	Plant Mix	Plant	14-130	6.33	3	05/03-06/03
				ARAC (6.3% AC-10)	Plant Mix	Plant	14-130	6.83	3	05/03-06/03
AR Project (I-40)	Task-1	ADOT	I-40	PG 58-22 (AR-Gap)	Plant Mix	Plant	14-130	11	2	11/01
				PG 58-22 (AR-Open)	Plant Mix	Plant	14-130	18	2	02/02
AR Project (I-17)	Task-2	ADOT	I-17	PG 58-22 (AR-Gap)	Plant Mix	Plant	14-130	5	2	11/02
					Plant Mix	Plant	14-130	8	2	11/02
					Plant Mix	Plant	14-130	11	2	11/02
				PG 64-16 (AR-Gap)	Plant Mix	Plant	14-130	5	2	11/02
					Plant Mix	Plant	14-130	8	2	11/02
					Plant Mix	Plant	14-130	11	2	11/02

Project	Task	Site ID	Sec/ Cell/Lane	Mix ID	Mix Type	Aging	Temp (F)	Va %	Rep	Testing Date
Alberta AR Project	-	-	ARAC	Alberta-ARAC	Plant Mix	Plant	14-130	9.4	2	11/02
		-	Conventional	Alberta-Conv.	Plant Mix	Plant	14-130	5.7	2	11/02
NCHRP 9-23	Field Calibration	MnRoad	Cell 16	Cell 16	Field Cores	Field	14-130	4.8	2	09/02-10/02
			Cell 18	Cell 18	Field Cores	Field	14-130	6	2	09/02-10/02
			Cell 21	Cell 21	Field Cores	Field	14-130	5	2	09/02-10/02
		WesTrack	Section 12	Section 12	Field Cores	Field	14-130	2.7	2	09/02-10/02
			Section 15	Section 15	Field Cores	Field	14-130	6	2	09/02-10/02
			Section 16	Section 16	Field Cores	Field	14-130	7.3	2	09/02-10/02
		ADOT	Flagstaff	Flagstaff	Field Cores	Field	14-130	4.9	2	09/02-10/02
			Perryville	Perryville	Field Cores	Field	14-130	9.7	2	09/02-10/02
			Kingman	Kingman	Field Cores	Field	14-130	11.4	2	09/02-10/02
NCHRP 9-23	Field Validation	LTPP	Aurora - CO	Aurora - CO	Field Cores	Field	14-130	Bad data	2	09/02-10/02
			Big-Timber - MT	Big-Timber - MT	Field Cores	Field	14-130	Bad data	2	09/02-10/02
			Charlotte - VT	Charlotte - VT	Field Cores	Field	14-130	Bad data	2	09/02-10/02
			Collins - MS	Collins - MS	Field Cores	Field	14-130	Bad data	2	09/02-10/02
			Delta - CO	Delta - CO	Field Cores	Field	14-130	Bad data	2	09/02-10/02
			Gillette - WY	Gillette - WY	Field Cores	Field	14-130	Bad data	2	09/02-10/02
			Groton - CT	Groton - CT	Field Cores	Field	14-130	Bad data	2	09/02-10/02
			Hebron - NV	Hebron - NV	Field Cores	Field	14-130	Bad data	2	09/02-10/02
			Opelika - AL	Opelika - AL	Field Cores	Field	14-130	Bad data	2	09/02-10/02
			Pullman - WA	Pullman - WA	Field Cores	Field	14-130	Bad data	2	09/02-10/02
			Ranchester - WY	Ranchester - WY	Field Cores	Field	14-130	Bad data	2	09/02-10/02
NCHRP 9-23	Verification Study	Maryland DOT	PG 64-22	PG 64-22	Lab Blend	6 hrs at 85C	14-130	7	2	10/02-11/02
					Lab Blend	8 hrs at 85C	14-130	7	2	10/02-11/02
					Lab Blend	14 hrs at 85C	14-130	7	2	10/02-11/02
					Lab Blend	6 hrs at110C	14-130	7	2	10/02-11/02
					Lab Blend	8 hrs at 110C	14-130	7	2	10/02-11/02
					Lab Blend	14 hrs at 110C	14-130	7	2	10/02-11/02
					Lab Blend	4 hrs at 135C	14-130	7	2	10/02-11/02
					Lab Blend	6 hrs at 135C	14-130	7	2	10/02-11/02
					Lab Blend	8 hrs at 135C	14-130	7	2	10/02-11/02
					Lab Blend	14 hrs at 135C	14-130	7	2	10/02-11/02

Project	Task	Site ID	Sec/ Cell/Lane	Mix ID	Mix Type	Aging	Temp (F)	Va %	Rep	Testing Date
NCHRP 9-23	Comp. vs. Uncomp.	WesTrack	Section 12	PG 64-22	Plant Mix	1 day in Oven	70 & 130	4	2	12/02
					Plant Mix	5 days in Oven	70 & 130	4	2	12/02
					Plant Mix	10 days in Oven	70 & 130	4	2	12/02
NCHRP 9-23	Lab Aging	WesTrack	Section 12	PG 64-22	Plant Mix	5 days at 80C in Oven	70 & 100	4	2	07/03-08/03
					Plant Mix	5 days at 85C in Oven	70 & 100	4	2	07/03-08/03
					Plant Mix	5 days at 90C in Oven	70 & 100	4	2	07/03-08/03
			Section 15	Section 15	Plant Mix	5 days at 80C in Oven	70 & 100	8	2	07/03-08/03
					Plant Mix	5 days at 85C in Oven	70 & 100	8	2	07/03-08/03
					Plant Mix	5 days at 90C in Oven	70 & 100	8	2	07/03-08/03
			Section 16	Section 16	Plant Mix	5 days at 80C in Oven	70 & 100	12	2	07/03-08/03
					Plant Mix	5 days at 85C in Oven	70 & 100	12	2	07/03-08/03
					Plant Mix	5 days at 90C in Oven	70 & 100	12	2	07/03-08/03
NCHRP 9-23	Lab Aging	ADOT	Perryville	Perryville	Plant Mix	5 days at 80C in Oven	70 & 100	7	2	07/03-08/03
				Perryville	Plant Mix	5 days at 85C in Oven	70 & 100	7	2	07/03-08/03
				Perryville	Plant Mix	5 days at 90C in Oven	70 & 100	7	2	07/03-08/03
			Kingman	Kingman	Plant Mix	5 days at 80C in Oven	70 & 100	7	2	07/03-08/03
				Kingman	Plant Mix	5 days at 85C in Oven	70 & 100	7	2	07/03-08/03
				Kingman	Plant Mix	5 days at 90C in Oven	70 & 100	7	2	07/03-08/03
			Flagstaff	Flagstaff	Plant Mix	5 days at 80C in Oven	70 & 100	7	2	07/03-08/03
				Flagstaff	Plant Mix	5 days at 85C in Oven	70 & 100	7	2	07/03-08/03
				Flagstaff	Plant Mix	5 days at 90C in Oven	70 & 100	7	2	07/03-08/03
NCHRP 9-23	Lab Aging	MnRoad	Cell - 16	Cell - 16	Plant Mix	5 days at 80C in Oven	70 & 100	8.2	2	07/03-08/03
					Plant Mix	5 days at 85C in Oven	70 & 100	8.2	2	07/03-08/03
					Plant Mix	5 days at 90C in Oven	70 & 100	8.2	2	07/03-08/03
			Cell - 18	Cell - 18	Plant Mix	5 days at 80C in Oven	70 & 100	5.1	2	07/03-08/03
					Plant Mix	5 days at 85C in Oven	70 & 100	5.1	2	07/03-08/03
					Plant Mix	5 days at 90C in Oven	70 & 100	5.1	2	07/03-08/03
			Cell - 21	Cell - 21	Plant Mix	5 days at 80C in Oven	70 & 100	5.1	2	07/03-08/03
					Plant Mix	5 days at 85C in Oven	70 & 100	5.1	2	07/03-08/03
					Plant Mix	5 days at 90C in Oven	70 & 100	5.1	2	07/03-08/03
NLA-ASU (Research Project)	E* MC Database for Lime Modified AC Mix	Two Guns	PG 64-22	0, 1, 2 & 3% Lime	Lab Blend	4 hrs STOA	14-130	7	3	9/03-12/03
		MD DOT	PG 64-22	0, 1 & 3% Lime	Lab Blend	4 hrs STOA	14-130	7	3	9/03-12/03
		Bidahouchi Base	PG 58-28	0, 1 & 2% Lime	Lab Blend	4 hrs STOA	14-130	7	3	9/03-12/03
		Salt River Base	PG 76-16	0, 1 & 2.5% Lime	Lab Blend	4 hrs STOA	14-130	7	3	9/03-12/03
		WesTrack	PG 64-22	0 & 1.5% Lime	Lab Blend	4 hrs STOA	14-130	7	3	9/03-12/03
		ALF	AC-5	0 & 3% Lime	Lab Blend	4 hrs STOA	14-130	7	2	9/03-12/03

Project 4: ADOT AC Thermal Fracture Characterization

Project Objective

The objective of this study was to develop a comprehensive database of the thermal fracture properties associated with typical ADOT mixtures. Eleven ADOT conventional mixtures were tested and analyzed. In addition, test results on four asphalt rubber mixes were included in the appendices for future comparison. Several test data and mixtures from other studies (Witczak et. al.) (2) were compared as quality control check studies to insure the overall accuracy of the test results obtained in this study.

Significance and Use

For thermal fracture analysis, the tensile creep and strength test data are fundamental material inputs required for the M-E PDG Level 1 and 2 implementation. Thermal cracking predictions are computed using an analysis module called TCMODEL, originally developed under SHRP research, which has been modified and recalibrated for inclusion in the M-E PDG.

The material inputs required for the fracture model are the tensile strength (at -10^{o}C) and the m-value. Tensile strength is directly obtained from the indirect tensile strength test. The m-value is related to the slope of the creep compliance master curve, and is computed in M-E PDG using compliance data obtained from the indirect tensile creep test. The values of creep compliance and tensile strength determined with this method are then used in a linear visco-elastic analysis to calculate the low temperature and fatigue cracking potential of the asphalt concrete.

In addition to the M-E PDG thermal fracture parameters, there are other potentially important parameters from the indirect tensile strength test that have been correlated to actual cracking values. These parameters include tensile strain at failure (εff), total fracture energy (Γfr), and fracture energy to failure (Γfa).

Summary of Test Method

All test specimens were prepared according to the test protocol University of Maryland (UMD) 9808 *Method for Preparation of Triaxial Specimens*. (3) All mixtures were short-term oven-aged for 4 hours at 135^{o}C, according to the AASHTO PP2 test method *Standard Practice for Short and Long Term Aging of Hot Mix Asphalt*, before compaction. The specimens were compacted with a Servopac gyratory compactor into a 150-mm diameter gyratory mold to approximately 160-mm in height. Approximately 5-mm was sawed from each end of the compacted specimen, and 3 test specimens approximately 38-mm thick were cut from each compacted specimen.

Both creep compliance and strength (indirect tensile mode) tests were carried out based on the procedure developed by Roque et al. (4), described in the draft indirect tensile tests protocol AASHTO TP9-02 (Project 4 , Appendix A). Two major modifications to the original protocol were made at ASU. The first change consisted of increasing the original LVDT's gage length of 1.5-in to a 3.0-in center-to-center spacing. This modification was implemented based on the recommendations from the NCHRP Project 1-28A. The second change consisted of using a temperature of -15^{o}C, instead of the recommended (-20^{o}C) low temperature. This modification was necessary due to the inability of the ASU environmental system to consistently reach -20^{o}C.

Vertical and horizontal LVDTs were mounted on the specimen for measuring the horizontal and vertical deformation during the indirect tensile creep test. The tests were conducted using three replicates at three temperatures: 0^{o}C (32^{o}F), -10^{o}C (14^{o}F), and -15^{o}C (5^{o}F). Based on the results from the three test temperatures, data was extrapolated to obtain creep compliance parameters for temperature of -20^{o}C.

The tensile creep was determined by applying a static load of fixed magnitude along the diametral axis of a specimen. The horizontal and vertical deformations measured near the center of the specimen were used to calculate tensile creep compliance as a function of time. Loads were selected to keep horizontal strains in the linear visco-elastic range during the creep test.

The tensile strength was determined immediately after conducting the tensile creep test by applying a constant rate of vertical deformation to failure. A total of four replicates were used during this test. One specimen per mixture was tested using both vertical and horizontal LVDTs, as recommended in the original Roque et al. (4) protocol. A modified method of measuring the tensile strength that also allows for the determination of the energy until failure and the total fracture energy was applied using three replicates per mixture. The vertical LVDTs were removed in this method to avoid possible damage in the post-failure phase of the test.

Experimental Plan

This project testing program included the complete thermal fracture characterization of 11 conventional mixtures designated by ADOT for inclusion into the overall main experiment. These mixtures used five different aggregates (Salt River ¾", Salt River Base, Bidahouchi ¾", Bidahouchi Base, and Two Guns), and four different binder types used throughout Arizona (PG 58-28, PG 64-22, PG 70-10, and PG 76-16). Table 8 presents general information about the mixtures used in the project. All were conventional dense graded mixtures.

Table 8. ADOT Project 4 - General Mixture Information

Aggregate	Binder	Mix Production Type
Salt River 3/4"	Chevron PG 76-16	Lab blended
	Chevron PG 64-22	Lab blended
	Navajo PG 70-10	Lab blended
Salt River Base	Chevron PG 76-16	Lab blended
	Chevron PG 64-22	Lab blended
	Navajo PG 70-10	Lab blended
Bidahouchi 3/4"	Chevron PG 64-22	Lab blended
	Paramount PG 58-28	Lab blended
Bidahouchi Base	Chevron PG 64-22	Lab blended
	Paramount PG 58-28	Lab blended
Two Guns	Paramount PG 64-22	Lab blended

Creep Compliance Results
No significant difference between the PG 64-22 and PG 70-10 binders for both gradations of the Salt River aggregate was observed. For the Salt River mixtures, the PG 76-16 binder indicated slightly higher creep compliance than the softer PG 64-22 binder. This observation contradicts the general rule of the HMA thermal fracture that the softer binder should yield higher creep compliance than the stiffer one. Higher than expected creep compliance has been found for the PG 58-28 binder compared to the PG 64-22.

Tensile Strength Results
In general, it was found that the softer the binder that was used to produce a mixture, the higher the measured tensile strength. It was also observed that the tensile strength values increased with decreasing temperature, with exception of the PG 70-10 binder. Another important observation was that the slope of the temperature-strength relationship was higher for mixtures with softer binders. This resulted in a minimal difference (4%) of the tensile strength between PG 58-28, PG 64-22, and PG 76-16 binders at 0^oC and a significant difference of 18% at -15^oC. More detailed results and explanation of these observations can be found on pg. 27~31 of Appendix 4, (Volume I of IV); *ADOT Asphalt Concrete Thermal Fracture Characterization*.

Regarding the influence of the aggregate gradation on the tensile strength, it was observed that coarser aggregate shows higher tensile strength when combined with very soft binder. This indicates that from the thermal fracture point of view the asphalt concrete base course should be mixed with soft binder i.e., PG 58-28. Finer aggregates (gradation 3/4") yield higher tensile strength when combined with stiffer binders and this good performance tends to improve with increasing binder stiffness.

Tensile Strain at Failure Results
Similar to the tensile strength results, it was found that the softer the binder, the higher the measured tensile strain at failure. It was also observed that the tensile strain at failure decreases with decreasing temperature. The slope of the temperature-strain relationship had a tendency to decrease with increasing stiffness of the binder. Generally, a larger difference between results was observed at high temperature (0^oC) compared to the -10^oC and -15^oC temperatures. A much higher loss of tensile strain at failure was observed in the zone between high and medium temperatures compared to the zone between medium and low temperatures.

Energy Until Failure Results of the ADOT Mixtures
It was observed that the softer the binder, the higher the measured energy-until-failure and slope of the temperature-energy relationship. It was also observed that energy value decreases with decreasing temperature.

Total Fracture Energy Results
Similar to the previous results, it was found that the softer the binder, the higher the total fracture energy and the slope of the temperature-energy relationship that were measured. It was also observed that the total energy values decreased when temperature was lowered. In general a higher loss of energy was observed between 0^oC and -10^oC compared to -10^oC and -15^oC interval.

Validation of the ASU - ADOT Indirect Tensile Tests Results

Based on the comparisons and analysis of the ASU-ADOT and the Roque-Buttlar data the following was concluded:

- In the case of the two binders that were compared in this study (PG 58-28 and PG 64-22), the creep compliance master curves from all seven mixtures were located within the "Roque-Buttlar data zone". It was also observed that Bidahouchi ¾" PG 58-28 mixture indicated relatively high creep compliance behavior and was located on the upper edge of the Roque-Buttlar data range. The rest of the ASU-ADOT mixtures were located near the center of the considered zone.
- The results of the statistical hypothesis testing indicated with a 90% confidence level, that the difference of the tensile strength between ASU-ADOT and Roque-Buttlar data was statistically insignificant at 0^oC and statistically significant at -10^oC. There are a few possible sources of the observed inconsistency of the statistical analysis results. The main problem was the small size of samples (populations). In one case there were only two available results from the ASU-ADOT study. The other problem was related with the high variance of the results. This inconsistency of the results does not allow for a definite conclusion that the ASU-ADOT tensile strength results are or are not comparable to the Roque-Buttlar data.
- The comparison of the measured versus the predicted creep compliance indicated that ASU-ADOT results correlate very well (R^2 = 0.89 and Se/Sy = 0.58) with the M-E PDG Level 3 prediction model. The newly revised prediction model for the combined data yielded a coefficient of determination R^2 = 0.83 and Se/Sy = 0.38.
- The comparison of the measured versus predicted tensile strength indicated that the M-E PDG proposed tensile strength prediction model underestimates the actual tensile strength of the ADOT HMA mixtures. A new prediction model built solely on the ASU-ADOT database was developed and yielded a coefficient of determination R^2 = 0.97 and Se/Sy = 0.18. The excellent correlation of the ASU-ADOT data might be an indicator that the modifications used by the ASU research team to evaluate (measure) the tensile strength may result in a significantly improved test protocol worth completing in future research efforts.

Project 5: ADOT AC Mixture Permanent Deformation Database

Project Objective

The objectives of this research work were twofold. First, build a repeated-load permanent-strain database collected from repeated-load dynamic testing. Second, analyze the database to generate a model to predict the permanent deformation behavior as a function of the number of load repetitions, binder and mixture properties. The developed model should be consistent with the constitutive models recommended for rut depth prediction within the M-E PDG.

Background

The permanent deformation models, used to predict the rut depth of the asphalt layer, usually relate the plastic strains to the number of load repetitions, as shown in equation (2). Other researchers use the plastic to resilient strain ratio as a function of the number of load repetitions and the temperature. The permanent deformation models used in the new M-E PDG are based on similar concepts. For asphaltic layers, the approach relates vertical resilient strains at the mid-depth of each layer, the number of traffic applications and the pavement temperature to layer plastic strains as shown in equation (3).

$$\varepsilon_p = aN^b \tag{2}$$

$$\frac{\varepsilon_p}{\varepsilon_r} = cN^d T^e \tag{3}$$

Where: ε_p = accumulated plastic strain at N repetitions of load; ε_r = resilient strain of the asphalt material; N = number of load repetitions; T = pavement temperature; and a, b, c, d, e = non-linear regression coefficients.

Database

The database used in this research was collected from 13 different projects. The initial sets of permanent deformation repeated-load dynamic test results were collected at the University of Maryland College Park (UMD). Further testing was later continued at Arizona State University (ASU). The database includes data for both plant mixes as well as lab-blended mixes. The database contains both confined and unconfined test data, including a total of 4990 data points (plastic strains & repetition pairs) from over 900 tested specimens at different load conditions. Table 9 lists the number of data points used in this study, obtained from testing conducted by four researchers at the University of Maryland and Arizona State University.

The repeated dynamic load testing results reported by Kaloush (5), Sullivan (6) and Quayum (7) were conducted on cylindrical specimens, 4 inches in diameter and 6 inches in height; while testing conducted by Leahy was performed on cylindrical specimens, 4 inches diameter and 8 inches in height. A haversine load of 0.1 sec and 0.9 sec dwell time was applied to the test specimens. A total of 181 data points of the 4990 total data points were obtained from confined testing conducted by Sullivan and Quayum.

The database covers a range of testing temperatures from 65°F to 150°F. Leahy used three different testing temperatures: 65 °F, 80 °F and 95 °F; Kaloush used higher testing temperatures ranging from 100 °F to 130 °F; while Sullivan and Quayum used a wider range of temperatures, from 80 °F to 150 °F.

Table 9 Number of Data Points by Researcher

Database Source	Test Conducted at	Number of Data Points
Leahy	UMD	1967
Kaloush	UMD and ASU	473
Sullivan	ASU	744
Quayum	ASU	1806
	Total Combined Database	4990

Preliminary Assessment of the Database

The database is composed of measured permanent strains at a range of load cycles. The cycles ranged from 1 to 200,000 cycles. In a preliminary assessment, the database was scanned in order to eliminate any cycles in the tertiary flow zone of the ε_p - N relationship. In addition, the starting cycle at which the permanent strain relation should be considered was investigated. The $\varepsilon_p/\varepsilon_r$ model in number of load cycles (N) and temperature (T), shown by equation (3), was regressed using data starting at a different number of cycles at a time, which included regressions with data starting at cycles greater than 1, 50, 100, 500 cycles and using all load cycles.

Figure 6 shows the coefficients of determination (R^2) for the regressions evaluated with different datasets depending on the initial number of cycles. Results showed that when considering the dataset that excluded the primary deformation zone (first cycle), the regression yielded the highest R^2. Based on this result, it was decided to use a database consisting of 4915 data points after eliminating the first cycle data.

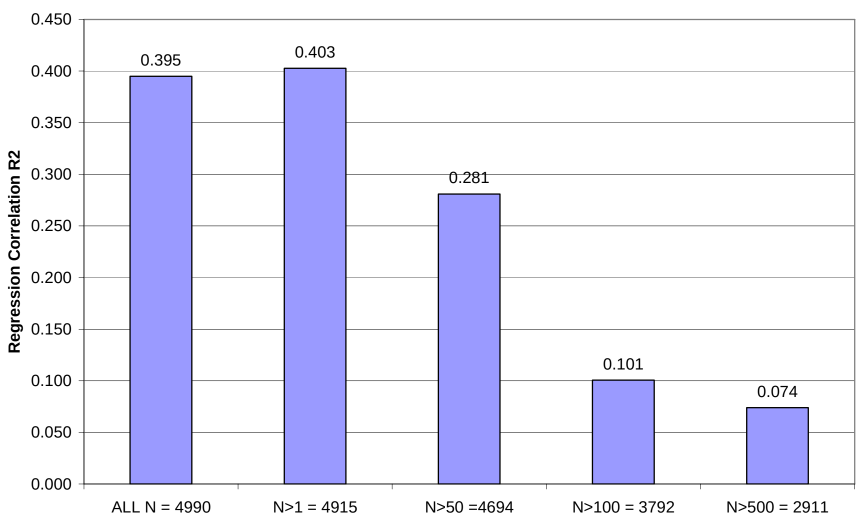

Figure 6 Regression Coefficients for Different Initial Cycles

Correlation Matrix Analysis and Stepwise Regression

The correlations of the slope and the intercept with individual parameters yielded poor results. This implied that the model required a transformation to improve the significance of the parameters considered. Accordingly, a correlation matrix was developed using the whole database for independent parameters using two dependent variables: the permanent strain, ε_p, and the permanent to resilient strain ratio, $\varepsilon_p/\varepsilon_r$. The analysis was aimed to recognize individual parameters that might have some impact on the permanent deformation prediction.

Table 10 shows results of the correlation matrix for ε_p and $\varepsilon_p/\varepsilon_r$. From Table 10 it was concluded that:

1. The ε_p variable had better correlations than the $\varepsilon_p/\varepsilon_r$ ratio with most of the variables at a 10% level of significance.
2. The most significant factors affecting the ε_p were found to be the resilient strain, the stress state, the dynamic shear modulus G^* and the phase angle δ, the number of load cycles, the testing temperature, the void in mineral aggregates (VMA), the viscosity at testing temperature, and the percentage of fines in the mixture.
3. The only factors that showed a significant correlation with the $\varepsilon_p/\varepsilon_r$ ratio were the number of load cycles, VMA, the effective binder content, and the percentage retained on sieve # 4.
4. The resilient strains (ε_r) have a significant effect on the prediction of the ε_p.
5. The use of the ε_p as a dependent variable would yield a better model than using the $\varepsilon_p/\varepsilon_r$ ratio to model permanent deformation using asphalt mixture properties.

Table 10 Coefficients of Correlation for ε_p and $\varepsilon_p/\varepsilon_r$

Variable	ε_p	$\varepsilon_p/\varepsilon_r$
ε_r	0.591	NA
T	0.252	0.042
N	0.134	0.104
η_T	-0.236	-0.057
δ	0.300	0.071
G^*	-0.267	-0.058
$G^*/\sin\delta$	-0.263	-0.058
V_a	0.074	0.039
V_{beff}	0.049	0.106
VMA	0.117	0.120
VFA	-0.056	-0.009
R_{34}	-0.051	-0.001
R_{38}	-0.022	-0.051
R_4	0.138	0.141
P_{200}	0.156	-0.038
Pstress	0.448	-0.067
Qstress	0.450	-0.065

Note: Shaded correlations are significant at a 10% level of significance.

The rutting prediction models commonly found in the literature use either permanent strain or permanent to resilient strain ratio as dependent variables. Based on the previous conclusion, it was decided to focus only on ε_p models and use ε_r as an independent variable (right hand side) in the ε_p model.

A stepwise regression analysis was run on different variables using the arithmetic, logarithmic and square of the logarithmic terms. Table 11 shows the results of the stepwise regression. The stepwise regression confirmed some of the findings shown in Table 11 on the correlation coefficients for individual parameters.

Table 11 Stepwise Regression log (ε_p)

Variable	Step	Multiple R	Multiple R^2	R^2 change	Variables included
$\log \varepsilon_r$	1	0.6960	0.4844	0.4844	1
$\log N$	2	0.8271	0.6840	0.1996	2
$\log R_{38}$	3	0.8423	0.7095	0.0255	3
$(\log N)^2$	4	0.8568	0.7341	0.0245	4
$\log P_{200}$	5	0.8681	0.7537	0.0196	5
$(\log R_4)^2$	6	0.8757	0.7668	0.0131	6
$\log Qstress$	7	0.8828	0.7794	0.0126	7
$(\log G^*/\sin\delta)^2$	8	0.8894	0.7911	0.0117	8
$\log Pstress$	9	0.8927	0.7969	0.0058	9
$\log VMA$	10	0.8941	0.7994	0.0025	10
$(\log Qstress)^2$	11	0.8954	0.8017	0.0023	11
$(\log P_{200})^2$	12	0.8966	0.8039	0.0022	12
$\log R_4$	13	0.8976	0.8057	0.0018	13
$(\log R_{38})^2$	14	0.8983	0.8070	0.0013	14
$(\log Pstress)^2$	15	0.8990	0.8082	0.0012	15
$(\log T)^2$	16	0.8996	0.8093	0.0011	16
$(\log R_{34})^2$	17	0.9001	0.8103	0.0010	17
$\log G^*/\sin\delta$	18	0.9006	0.8110	0.0008	18
$(\log VMA)^2$	19	0.9009	0.8116	0.0006	19
$\log T$	20	0.9012	0.8121	0.0005	20
$\log R_{34}$	21	0.9013	0.8124	0.0003	21

The most significant variables found were the resilient strain, number of load repetitions, the stress state (log *Qstress*), the aggregate gradation, the binder property $(\log (G^*/\sin \delta))^2$, and to a lesser extent, the VMA and the log *Pstress*.

Model Regression Analysis
A set of models was investigated based on the significance of the variables obtained from the stepwise regression analysis shown in Table 11. These models were developed in order to check the interaction between some of the variables as well as to find the significance level of such variables. The models studied are shown in Table 12.

The following equation represents the recommended model (model 24) in Table 12 .

$$\log \varepsilon_p = 1.681 + 0.671 \log \varepsilon_r + 0.338 \log N - 2.673 \log P_{200} - 1.611 \log R_{38} - 1.376 \log Pstress + 1.620 \log Qstress - 0.077 \left(\log \frac{G^*}{\sin \delta} \right)^2 + 1.007 (\log R_4)^2 + 0.540 \log VMA \quad (4)$$

The model presented in the above equation yielded a statistically significant model with R^2 = 78%, has only two quadratic terms and the least number of the significant independent variables. The independent variables included in the model are the resilient strain, number of cycles, aggregate gradations, stress state, binder shear modulus and a volumetric property. Figure 7 shows the predicted permanent strains plotted versus the measured permanent strains.

A sensitivity analysis was conducted using the recommended model. Reasonable trends were found by varying each of the nine variables used in the predictive model. The trends were consistent with engineering experience and known field performances. Details of the sensitivity analysis are provided in the Appendix 5.

Table 12 Regression Parameters for ε_p Models

Variable	Coeff.	Model Equation															
		12	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**
	A_1	2.523	2.689	3.108	2.669	1.574	1.762	-0.445	0.519	0.060	0.025	-0.374	-1.004	1.681	-1.973	-1.894	-0.870
$log\ \varepsilon_r$	A_2	0.661	0.060	0.653	0.669	0.693	0.673	1.027	0.808	0.842	0.723	0.688	0.736	0.671	0.683	0.767	0.767
$log\ N$	A_3	0.877			0.886			1.003			0.876	0.885	0.896	0.338	0.896	0.940	0.3333
$log\ P_{200}$	A_4	-5.885	-5.798	-6.061	-6.171	-2.568	-2.481	-1.371	-1.750	-2.360	-1.15	-1.589		-2.673	-2.645	-2.649	-2.663
$log\ R_{38}$	A_5	-1.570	-1.531	-1.526	-1.577	-1.591	-1.563	-1.409	-1.492	-1.603	-0.093		-0.345	-1.611	-1.630	-1.618	-1.608
$log\ Pstress$	A_6	-1.802	-2.679	-0.047	-1.773	-2.691	0.738	-1.586	-2.596	-2.302	-1.517	-1.519	-2.058	-1.376	-1.558	-1.506	-1.287
$log\ Qstress$	A_7	2.061	2.813	0.293	2.035	2.809	-0.494	1.578	2.604	-1.922	1.638	1.707	2.132	1.62	1.785	1.694	1.489
$log\ G^*/\sin\delta$	A_8	0.083	0.203	-0.046												-0.241	-0.257
$(log\ N)^2$	A_9	-0.091	-0.091	-0.079	-0.093	-0.096	-0.077	-0.114	-0.111	-0.112	-0.093	-0.094	-0.099		-0.094	-0.103	
$(log\ G^*/\sin\delta)^2$	A_{10}	-0.096	-0.101	-0.108	-0.076	-0.071	-0.110				-0.057	-0.066	-0.033	-0.077	-0.072		
$(log\ R_4)^2$	A_{11}	1.059	0.997	0.999	1.070	1.000	0.980	0.771	0.869	0.974		0.352	0.228	1.007			
$(log\ P_{200})^2$	A_{12}	2.121	2.157	2.301	2.260												
$log\ VMA$	A_{13}							0.485		0.310	1.005	0.660	0.898	0.540	0.606	0.563	0.482
$log\ R_4$	A_{14}														3.366	3.314	
$log\ N$	B_1		0.754	0.499		0.806	0.514		0.942	1.125							
$G^*/\sin\delta$	B_2		0.00003	0.028		0.00002	0.027		-0.00007	-0.024							
VMA	B_3		0.006	0.121		0.006	0.116		0.005	0.033							
$Pstress$	B_4		0.005	-0.391		0.005	-0.638		0.005	-0.663							
$Qstress$	B_5		-0.004	0.393		-0.005	0.633		-0.0049	0.626							
Number of linear terms		7	11	11	6	10	10	7	10	12	7	6	6	7	8	9	8
Number of quad. terms		4	4	4	4	3	3	2	2	2	2	3	3	2	2	1	0
S_e		0.291	0.285	0.285	0.291	0.288	0.286	0.325	0.304	0.307	0.319	0.310	0.329	0.305	0.291	0.298	0.314
S_e/S_y		0.449	0.440	0.440	0.449	0.444	0.442	0.502	0.469	0.473	0.492	0.479	0.508	0.470	0.448	0.406	0.485
R^2		0.799	0.807	0.807	0.798	0.803	0.805	0.750	0.780	0.776	0.759	0.771	0.743	0.780	0.799	0.789	0.765

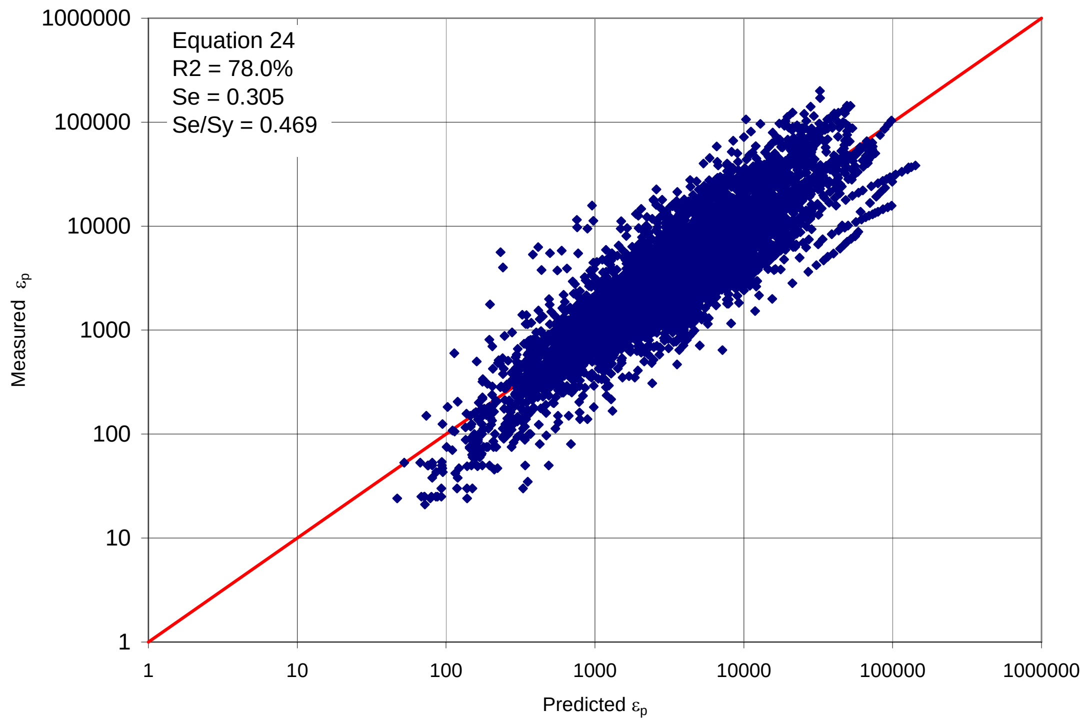

Figure 7 Predicted vs. Measured ε_p Model (equation 24)

Project 6: ADOT HMA Fatigue Characterization Database

Project Objective

The objectives of Project 6 were to develop a comprehensive database of the typical ADOT HMA mixture fracture (fatigue) properties and parameters for use in the implementation of the M-E PDG system and to develop a fatigue cracking model specific for the ADOT HMA mixtures.

Background

Load associated fatigue cracking is one of the major distress types occurring in flexible pavement systems. Fatigue cracks are a series of longitudinal and/or interconnected cracks caused by the repeated application of wheel loads that results in fatigue failure of the hot mix asphalt (HMA) surface and/or base mixtures. This type of cracking generally starts as short longitudinal cracks in the wheel path and progresses to an alligator cracking pattern (interconnected cracks).

The literature has numerous models to characterize fatigue in asphalt layers. The most common model form used to predict the number of load repetitions to fatigue cracking is a function of the tensile strain and mix stiffness (modulus). The basic structure for most of the models developed and presented in the literature for fatigue characterization is of the following form (Monismith, C. L et al. (8)).

$$N_f = A_f \, K_1 \left(\frac{1}{\varepsilon_t} \right)^{k_2} \left(\frac{1}{E} \right)^{k_3} \qquad (5)$$

Where: N_f = number of repetitions to fatigue cracking; ε_t = tensile strain at the critical location; E = stiffness of the material; and k_1, k_2, k_3 = laboratory calibration parameters.

In the laboratory, two types of controlled loading are generally applied for fatigue characterization: constant stress and constant strain. In constant stress testing, the applied stress during the fatigue testing remains constant. As the repetitive load causes damage in the test specimen, the strain increases resulting in a lower stiffness with time. In a constant strain test, the strain remains constant with the number of repetitions. Because of the damage due to repetitive loading, the stiffness is reduced as a function of load repetitions and the stress must be reduced to maintain constant strain.

The constant stress type of loading is considered applicable to thick pavement layers usually more than 8 inches, whereas the constant strain loading is applicable to thin layers of less than 2 inches. For HMA thicknesses between these extremes, fatigue behavior is governed by a mixed mode of loading, mathematically expressed as some model yielding intermediate fatigue prediction to the constant strain and stress conditions.

Literature Review Search

The researchers reviewed the literature to document previous and existing asphalt concrete fatigue studies needed to accomplish the objectives of this study. The literature reviewed included both the mechanistic empirical approach and energy based approach.

Specimen Preparation Method Investigation and Development

Specimen preparation using a simple compaction method was developed and investigated to ensure the uniformity of air void content throughout specimen length and depth. The compaction effort required to reach a certain amount of air void was determined.

Test Program and Plan

A comprehensive test plan was developed to include typical conventional and modified ADOT asphalt concrete mixtures. Three Salt River Base (SRB) mixes, three Salt River ¾" (SR3/4) mixes, two Bidahouchi Base mixes, two Bidahouchi ¾" mixes, Two Guns lab blend and rubber asphalt mixes, and ADOT asphalt rubber gap graded mixtures were tested. Table 13 shows the combination of mixes tested. All these mixes were tested at the following conditions:

- Three temperature levels: 100^{o}F, 70^{o}F, and 40^{o}F (37.8^{o}C, 21.1^{o}C, and 4.4^{o}C),
- Two load modes: controlled strain and controlled stress. Constant strain with 6 to 10 levels ranging from 200 μ strain to 1750 μ strain and constant stress with 6 to 10 levels ranging from 300 kPa to 3000 kPa (2000 psi -20000 psi),
- Six to ten levels of strain or stress,
- One air void content of 7 percent, and,
- One replicate for each factor combination.

Table 13 Features of ADOT SRB and Bidahouchi Base Typical Asphalt Fatigue Experiment

Item	Levels	Description
Aggregate Type	2	Salt River Base Bidahouchi Base
Asphalt Type	5	Chevron 76-16 Chevron 64-22 Navajo 70-10 Paramount 58-28 Chevron 64-22
Asphalt Content	1	Design content for each asphalt type
Air Voids Level	1	7%
Strain Levels & Stress Level	8-10	From 200-1750 µ strains From 2000-20000 psi
Replicates at each Strain Interval	1	One
Test Temperature	3	100,70, and 40^{o}F (37.7, 21.1, and 4.4^{o}C)
Frequency	1	10 Hz
Load Control	1	Controlled Strain (Haversine) Controlled Stress (Sinusoidal)
Specimen Size	1	2 in (51 mm) Height 2.5 in (63.5 mm) Width 15 in (381 mm) Length
Total Number of Mixes Tested	5	
Total Number of Specimens Tested	240-300	

Initial flexural stiffness was measured at the 50th load cycle. Fatigue life or failure under control strain was defined as the number of cycles corresponding to a 50% reduction in the initial stiffness. However, the loading on most specimens was extended to reach a final stiffness of 20-30% of the initial stiffness instead of the 50% required by AASHTO TP8 and SHRP M-009 in order to study more material characteristics.

For the ADOT asphalt rubber, the following conditions were used as shown in Table 14:

- Air voids: 8% for gap graded specimens.
- Load condition: 8 constant strain levels ranging from 300-1750 µ strain and 8 controlled stress levels.
- Load frequency: 10 Hz.
- Test temperature: 100^{o}F, 70^{o}F, and 40^{o}F (37.8^{o}C, 21.1^{o}C, and 4.4^{o}C).

Table 14 Features of Asphalt Rubber Gap Graded Fatigue Experiment

Item	Levels	Description
Aggregate Type	1	Salt River
Asphalt Type	1	PG 58-22
Asphalt Content	1	7.5%
Air Voids Level	1	8%
Strain Levels	8-10	From 300-1750 μ strains
Replicates at each Strain Interval	1	One
Temperature	3	100, 70, and 40^{o}F
Frequency	1	10 Hz
Load Control	2	Controlled Strain (Haversine) Controlled Stress (Sinusoidal)
Specimen Size	1	2 in (51 mm) Height
		2.5 in (63.5 mm) Width
		15 in (381 mm) Length
Total Number of Mixes Tested	1	
Total Number of Specimens Tested	48	

Several specimens that fell outside of the desired air void content ±1.0% had to be discarded. As with ADOT conventional mixes, tests were performed according to the AASHTO TP8, and SHRP M-009 procedure.

Table 15 shows the experimental and testing program adopted in this research work. A total of 248 conventional mixes were tested as well as 48 asphalt rubber mixes.

The following variables, for one set of specimens under controlled strain and one set under controlled stress, were computed and studied:

1. Stiffness versus Number of Repetitions
2. Dissipated Energy versus Number of Repetitions
3. Cumulative Dissipated Energy versus Number of Repetitions
4. Phase Angle versus Number of Repetitions
5. Loss Modulus (Stiffness * Sin (Phase Angle)) versus Number of Repetitions
6. Energy Ratio (N*wo/w) versus Number of Repetitions
7. Energy Ratio (E*N) versus Number of Repetitions
8. The New Energy Ratio (N*E/Eo) versus Number of Repetitions

Note: N=Load Cycle, Wo=Initial Dissipated Energy, W=Dissipated Energy at Load Cycle, Eo=Initial Energy, E=Energy at Load Cycle

These variables were used for the analysis conducted to develop the ADOT fatigue model.

Table 15 Experimental and Testing Program

Mix Type			Load Control						Total # of Specimens
			Controlled Strain			Controlled Stress			
			40 F	70 F	100 F	40 F	70 F	100 F	
ADOT AC Mixes	Salt River Base 7% Va	Chevron 76-16	8*	8	8	8	8	8	48
		Chevron 64-22	8	8	8	8	8	8	48
		Navajo 70-10	8	8	8	8	8	8	48
	Bidahochi Base 7% Va	Chevron 64-22	8	8	8	8	8	8	48
		Paramount 58-28	8	8	8	8	8	8	48
ADOT AR Mixes	ARAC I-17 8% Va	PG 58-22**	8	8	8	8	8	8	48

*8 to 10 beam specimens were used to accurately define the strain repetition relationship.

** PG58-22 is base binder then blended with CR A-2 binder

Fatigue Model Development

Fatigue models for all typical ADOT asphalt concrete mixtures and ADOT Asphalt rubber gap graded mixtures were developed. Regression coefficients were obtained for each mix as well as for combined mixes as shown in Table 16.

Table 16 Regression coefficients k1, k2 and k3 for ADOT mixes

MIX TYPE	LOAD CONTROL	%So AND N	K1	K2	K3	R^2
SRB CHEVRON 76-16	STRAIN	50%N50	1.32E-03	4.9536	1.5306	0.9747
	STRESS	50%N50	7.77E-07	4.3611	0.8578	0.9993
SRB CHEVRON 64-22	STRAIN	50%N50	4.99E-07	5.1193	1.0271	0.6999
	STRESS	50%N50	4.92E-09	4.4502	0.4735	0.9878
SRB NAVAJO 70-10	STRAIN	50%N50	4.02E-15	6.4674	0.6409	0.8778
	STRESS	50%N50	1.41E-07	2.9598	-0.1434	0.8203
BIDAHOUCHI BASE PARAMOUNT 58-2	STRAIN	50%N50	4.80E-13	5.5656	0.3194	0.7948
	STRESS	50%N50	8.48E-05	3.7209	0.7248	0.9160
BIDAHOUCHI BASE PG 64-22	STRAIN	50%N50	2.60E-17	6.0596	-0.1635	0.9935
	STRESS	50%N50	5.78E-10	3.8443	-0.1286	0.9592
AR I-17 PG 58-22	STRAIN	50%N50	1.98E-01	3.7100	1.0273	0.8335
	STRESS	50%N50	3.19E-14	10.1531	3.0044	0.9881
ALL MIXES	STRAIN	50%N50	3.57E-03	2.6532	0.2073	0.2764
	STRESS	50%N50	8.79E-01	1.8189	0.1832	0.2250
ALLSRB & BIDAHOUCHI MIXES	STRAIN	50%N50	3.69E-04	2.9753	0.2439	0.2803
	STRESS	50%N50	2.61E-03	2.2909	0.0729	0.4376
ALL BIDAHOUCHI MIXES	STRAIN	50%N50	4.26E-18	6.6773	0.1136	0.6986
	STRESS	50%N50	4.47E-07	4.4493	0.7857	0.8011
ALL SRB MIXES	STRAIN	50%N50	1.46E-03	3.1103	0.4595	0.4658
	STRESS	50%N50	5.54E-02	2.2817	0.3220	0.4771

Where:

$N_f = K1 * (1/\varepsilon_t)^{K2} * (1/So)^{K3}$

N_f = Fatigue life (cycles)

ε_t = Initial strain in/in

S_o = Initial stiffness (psi)

K1,k2,k3 = Laboratory calibration Parameters

Rating System	R^2
Excellent	>0.90
Good	0.70-0.89
Fair	0.40-0.69
Poor	0.20-0.39
Very Poor	< 0.19

Finally, all mixes were studied and a Global Fatigue Model was produced for ADOT mixtures. The newly developed fatigue models can be used as surrogate models to predict the fatigue life of any ADOT mix with a high degree of precision. A simple way for improving the existing fatigue model, to best-fit ADOT mixes, was introduced with good results. The recommended general fatigue model under constant strain is:

$$N_f = 2.7522E\text{-}12 * EXP(-0.001874 * G_b^* SIN\delta) * (1/\varepsilon)^{5.4525} * (1/So)^{0.3234} \quad (6)$$

$R^2 = 0.64$, Se/Sy = 0.58

The recommended general fatigue model under constant stress is:

$$N_f = 3.0246E\text{-}07 * EXP((-0.0025*G_b^* SIN\delta) + 0.2380 * V_b) * (1/\varepsilon)^{4.255} * (1/So)^{0.783} \quad (7)$$

$R^2 = 0.81$, Se/Sy = 0.45

The recommended energy model under constant strain is:

$$N_f = 727.89 * EXP(-0.00152 * G_b^*) * (1/w_o)^{1.9053} \quad (8)$$

$R^2 = 0.25$, Se/Sy = 0.87

The recommended energy model under constant strain is:

$$N_f = 1.51E08 * EXP(-1.0872*A - 0.8488 * VA) * (1/w_o)^{2.2077} \quad (9)$$

$R^2 = 0.67$, Se/Sy = 0.58

Project 7: ADOT Implementation of Simple Performance Test

Objectives

The objective of this project was to develop a comprehensive field validation of the recommended approach for the Simple Performance Test. Tests to produce the F_n and F_t data, ε_p (permanent strain at flow), ε_r (recoverable strain at flow), $\varepsilon_p/\varepsilon_r$ (from F_n test) and compliance (from F_t test), and mixture data related to all F_n and F_t tests were conducted under Project 7.

Materials Investigated

The total tested mixture matrix consisted of AC mixtures from Salt River Base mixes (PG 64-22, 70-10 and 76-16 lab blend mixes), Salt River ¾″ mixes (PG 64-22, 70-10 and 76-16 lab blend mixes), Bidahouchi Base mixes (PG 58-28, and 64-22 lab blend mixes), Bidahouchi ¾″ mixes (PG 58-28, and 64-22 lab blend mixes), Salt River ¾″ mixes (PG 64-22, 70-10 and 76-16 lab blend mixes), US-60 (1st and 2nd lift plant mixes) and Two Guns (PG 64-22 lab blend mixes). The Advanced Pavement group at ASU had also conducted many other F_n and F_t tests under Task C of NCHRP Project 9-19 *Superpave Support and Performance Models Management*, which includes ADOT and non-ADOT mixes. The non-ADOT mixes included mixes from WesTrack (plant mix) and FHWA-ALF (lab blend and field cores), while the ADOT mixes included mixes from I-10 (plant mix) and Salt River Base mixes (lab blend). This additional data is also included in the project database.

Testing Program

Static creep and repeated load tests, confined and unconfined, were conducted using at least two replicate test specimens for each mixture. All tests were performed on on cylindrical specimens, 4 inches in diameter and 6 inches in height. For the static creep tests, a static constant load was applied until tertiary flow occurred. For the repeated load tests, a haversine pulse load of 0.1 sec and 0.9 sec dwell (rest time) was applied for a target of 300,000 cycles. This number was smaller if the test specimen failed under tertiary flow before reaching this target level.

All tests were conducted within an environmentally controlled chamber throughout the testing sequence (i.e., temperature was held constant within the chamber to $\pm 1\ ^{o}$F throughout the entire test).

Results

The flow number was determined from the results of the repeated load tests as the starting point, or cycle number, at which tertiary flow occurred. The flow time was determined from the results of the static creep tests as the time when shear deformation, under constant volume (tertiary flow), started.

The flow number and flow time data for the mixtures investigated are summarized in appendix 7, part D.

1. APPENDIX-A: Summary of major F_n and F_t testing conducted on conventional AC mixtures at ASU during 1999-2005.
2. APPENDIX-B: F_n Database of Projects #5 and #7 of the ASU-ADOT research program titled *Development of Performance Related Specifications for Asphalt Pavements in the State of Arizona*.
3. APPENDIX-C: F_n Database of Task C of NCHRP 9-19 Project *Superpave Support and Performance Models Management*.
4. APPENDIX-D: F_t Database of Projects #5 and #7 of the ASU-ADOT research program.
5. APPENDIX-E: F_t Database of Task C of NCHRP 9-19 Project *Superpave Support and Performance Models Management*.

UNBOUND MATERIALS

Project 8: ADOT Unbound Materials Modulus Database

Objectives

The objective of this study was to develop a resilient modulus predictive model for ADOT unbound materials (coarse-grained and fine-grained), capable of estimating changes in modulus as a function of changes in state of stress, moisture and density. This model can be used in pavement response models and mechanistic-empirical design methods and fulfills key requirements of accuracy, computational stability and implementability in existing mechanistic-empirical design methodologies.

Materials Investigated

A total of 96 resilient modulus laboratory tests were carried out on 8 materials (4 bases and 4 subgrades) typically used in highway construction projects in Arizona. The routine properties of these materials are summarized in Tables 17 and 18.

Testing Program

In order to achieve the objectives of this study, the laboratory testing program consisted of two major tasks: routine soil classification tests and resilient modulus tests. Routine tests included sieve analysis, plasticity, specific gravity, moisture-density curves and California Bearing Ratio (CBR) tests. In the laboratory, tests for resilient modulus take into account the state of stress by applying different combinations of confining pressure and deviatoric stress to the test specimens. To account for moisture changes similar to those occurring in the field, test specimens initially compacted at optimum conditions (optimum moisture content and maximum dry density) were either soaked or dried, and then tested. Density was considered by compacting specimens at two different densities corresponding to two compactive efforts: i.e., standard and modified. All tests were conducted according to the NCHRP 1-28A (harmonized) resilient modulus test protocol in the ASU Advanced Pavement Laboratory.

Results

Based on the testing results, a resilient modulus predictive model that includes the effects of moisture and state of stress upon the resilient modulus was developed:

$$M_R = 10^{\log_{10} a + \frac{\log_{10} b - \log_{10} a}{1+EXP\left(\beta + k_w \cdot \left(w - w_{opt}\right)\right)}} \cdot k_1 \cdot p_a \cdot \left(\frac{\theta}{p_a}\right)^{k_2} \cdot \left(\frac{\tau_{oct}}{p_a} + 1\right)^{k_3} \qquad (10)$$

Where: $M_R =$ resilient modulus: p_a = atmospheric pressure; k_1, k_2, k_3 = regression constants; θ = bulk stress; τ_{oct} = octahedral shear stress; w = gravimetric moisture content expressed in decimal; w_{opt} = gravimetric optimum moisture content corresponding to standard compaction energy in decimal; M_{Ropt} = resilient modulus at optimum moisture content and maximum dry density corresponding to standard compaction energy; a = the minimum value of the ratio M_R/M_{Ropt}; b = maximum value of the ratio M_R/M_{Ropt}; β = location parameter calculated from:

$$\beta = \ln_e\left(\frac{-\log_{10}(b)}{\log_{10}(a)}\right) \tag{11}$$

Table 17 Routine Properties of the ADOT Subgrade Soils

Property	Specification	Material			
		FCSG	PVSG	SCSG	YSSG
Source		Flagstaff Area	Phoenix Metro Area	Sun City	Yuma Area
Soil Classification	AASHTO	A-2-6	A-2-4	A-2-6	A-1-a
	Unified	SC	SC	SC	GP
Liquid Limit (LL)	ASTM D 4318-98	38.8	28.7	32.7	--
Plastic Limit (PL)	ASTM D 4318-98	21.7	18.7	20.6	--
Plasticity Index (PI)		17.2	9.9	12.1	NP
% Fines		31.5	21.6	25.0	1.2
Optimum Moisture Content, (Standard)	ASTM D 698-91	19.0	11.3	10.6	11.0
Maximum Dry Density, γ_{dmax} (pcf) (Standard)	ASTM D 698-91	102.2	123.4	121.0	112.4
Degree of Saturation @ OMC (%)		78.3	81.9	73.3	61.1
Specific Gravity (Gs)	ASTM D 854-92	2.719	2.719	2.689	2.665
CBR @ OMC (%)		19.0	28.0	57.0	42.0

Table 18 Routine Properties of ADOT Base Materials

Property	Specification	Material			
		GMAB2	SRAB2	GLAB2	PRAB2
Source		Grey Mountain	Salt River	Globe	Prescott
Classification	AASHTO	A-1-a	A-1-a	A-1-a	A-1-a
Plasticity Index (PI)		NP	NP	NP	NP
% Fines		5.1	3.8	6.5	6.4
Optimum Moisture Content, OMC (%) (Modified)	ASTM D 1557-91	6.4	5.0	5.4	6.0
Maximum Dry Density, γ_{dmax} (pcf) (Modified)	ASTM D 1557-91	139.0	135.0	142.0	143.8
Degree of Saturation @ OMC (%)		61.8	56.7	64.4	89.1
Specific Gravity (Gs)	ASTM D 854-92	2.895	2.674	2.812	2.728
CBR @ OMC (%)		100.0	98.0	105.0	69.0

Model parameters were generated for each of the eight unbound materials tested in this study. In addition, a set of coefficients was generated for the four A-1-a base materials as a group. It is recommended to use these coefficients for any Arizona base material that fulfills the ADOT plasticity and gradation criteria for AB2 materials and for which resilient modulus laboratory tests will not be performed.

For the group of plastic subgrades (A-2 materials), a similar set of parameters was generated, however they were limited to values for *a*, *b* and k_w. The limited set of parameters cannot be used to estimate the resilient modulus at any state of moisture and stress but can be used to estimate changes in resilient modulus as a function of changes in moisture, when the resilient modulus at optimum moisture content is known. The following equation is used in this case:

$$M_R = 10^{\log_{10} a + \frac{\log_{10} b - \log_{10} a}{1 + EXP\left(\beta + k_w \cdot (w - w_{opt})\right)}} \cdot M_{Ropt} \tag{12}$$

Table 19 summarizes the model parameters for the eight ADOT unbound materials as well as the grouped materials. In addition, a predictive algorithm – the CBR-k2-k3 model – for the estimation of the regression constants k2 and k3 from CBR values was developed and is described by the following set of equations:

$$M_R = F_u \cdot k_1 \cdot p_a \cdot \left(\frac{\theta}{p_a}\right)^{k_{2CBR}} \cdot \left(\frac{\tau_{oct}}{p_a} + 1\right)^{k_{3CBR}} \tag{13}$$

Where:

$$k_{2CBR} = \frac{\log(\lambda_1 \cdot CBR(\%)^{\lambda_2}) - \log F_u - \log(k_1 \cdot p_a)}{\log\left(\frac{30 \cdot CBR(\%)}{p_a}\right)} \tag{14}$$

and

$$k_{3CBR} = \frac{\log(\lambda_3 \cdot CBR(\%)^{\lambda_4}) - \log F_u - \log(k_1 \cdot p_a) - k_{2CBR} \cdot \log\left(\frac{20 \cdot CBR(\%)}{p_a}\right)}{\log\left(\frac{2.357 \cdot CBR(\%)}{p_a} + 1\right)} \tag{15}$$

Where:

- CBR = California Bearing Ratio;
- λ_1, λ_2, λ_3, λ_4 = material parameters summarized in Table 20 for A-1 and A-2 type materials by AASHTO classification;
- F_u = environmental adjustment factor, equals the ratio of resilient modulus at any moisture/density to resilient modulus at optimum moisture content and maximum dry density as obtained from the *standard* compaction curve. (F_u = 1 at optimum conditions. F_u can be estimated depending on the type of material. Typical F_u vs. (w-w_{opt}) curves were developed for all the Arizona materials tested in this study);

- k_1 = regression parameter, (for the materials involved in this study k_1 values ranged between 1000 to 1500 for A-1 type materials and between 500 to 800 for the A-2 type materials).

The model may prove to be a very powerful tool for predicting stress and moisture dependent resilient modulus from CBR test results. It showed a very good accuracy ($R^2 > 0.88$) over a range of states of stress.

Table 19 Arizona Database of Model Parameters*

Material ID	AASHTO	USCS	*a*	*b*	k_w	β	k_1	k_2	k_3	$w_{opt\ std}$ %
Phoenix Valley Subgrade	A-2-4	SC	0.24	41.88	67.255	0.974	467	0.358	-0.686	11.3
Yuma Area Subgrade	A-1-a	GP	1.00	94.01	82.757	8.714	1,468	0.838	-0.888	11.0
Flagstaff Area Subgrade	A-2-6	SC	0.31	10.93	74.489	0.722	634	0.187	-0.855	19.0
Sun City Subgrade	A-2-6	SC	0.13	19.22	53.166	0.360	747	0.224	-0.104	11.3
Grey Mountain Base	A-1-a	GW	0.00	2096.40	2.559	-0.539	1,423	0.758	-0.288	6.7
Salt River Base	A-1-a	SP	0.59	2096.41	22.401	2.666	1,170	0.919	-0.572	6.9
Globe Area Base	A-1-a	SP-SM	0.68	2096.44	35.787	2.981	1,032	0.830	-0.307	6.7
Prescott Area Base	A-1-a	SP-SM	1.00	2096.45	144.223	8.711	1,092	0.784	-0.236	6.3
ADOT A-1-a AB2 Base Materials	A-1-a	SP-SM	0.60	2096.65	24.221	2.721	1,075	0.841	-0.305	6.7
ADOT A-2 Subgrade Materials	A-2	SC	0.22	21.79	58.965	0.699	-	-	-	-

* All parameters are dimensionless

Table 20 Fitting Parameters λ_I

Group of Materials	λ_1	λ_2	λ_3	λ_4
A-1	52,337	0.7325	3,787.4	1.0266
A-2	720.59	1.201	416.36	1.0735

Project 9: ADOT Unbound Materials Permanent Deformation Database and Development of Universal Permanent Strain Model

Objectives
The main objective of this research was to develop a universal, mechanistic constitutive law to predict the permanent deformation (rutting) of the ADOT pavement subgrade soils under repeated traffic loads. The secondary objective was to build a database of typical model responses and parameters for the investigated materials.

Materials Investigated
The materials studied in this research represent four typical subgrade soils for pavement construction in some areas in Arizona. The routine properties of these materials are summarized in Table 21.

Table 21 Routine Properties of the ADOT Subgrade Soils

Property	Specification	Material			
		FCSG	PVSG	SCSG	YSSG
Source		Flagstaff Area	Phoenix Metro Area	Sun City	Yuma Area
Soil Classification	AASHTO	A-2-6	A-2-4	A-2-6	A-1-a
	Unified	SC	SC	SC	GP
Liquid Limit (LL)	ASTM D 4318-98	38.8	28.7	32.7	--
Plastic Limit (PL)	ASTM D 4318-98	21.7	18.7	20.6	--
Plasticity Index (PI)		17.2	9.9	12.1	NP
% Fines		31.5	21.6	25.0	1.2
Optimum Moisture Content, OMC (%)	ASTM D 698-91	19.0	11.3	10.6	11.0
Maximum Dry Density, γ_{dmax} (pcf)	ASTM D 698-91	102.2	123.4	121.0	112.4
Degree of Saturation @ OMC (%)		78.3	81.9	73.3	61.1
Specific Gravity (Gs)	ASTM D 854-92	2.719	2.719	2.689	2.665

Testing Program
A laboratory testing program was developed based on the findings of a comprehensive literature search. The laboratory test program consisted of three main tasks as follows:

The first task involved standard (routine) soil classification tests. These tests included gradation, Atterberg limits, specific gravity, and moisture-density compaction curves. The second laboratory task was the completion of static shear strength triaxial tests on the investigated materials at three different moisture levels. These tests were conducted to determine the failure stress (strength) of the materials investigated. A series of unconsolidated, undrained (UU) triaxial tests were performed on 4 inch diameter by 8 inch high cylindrical specimens. The shear tests were conducted at three to five different confining stresses (0 psi, 5 psi, 10 psi, 15 psi, and 20 psi). To take into account the expected range of moisture variations in the field, all specimens were initially compacted at the target maximum dry density and optimum moisture content values according to the Standard Proctor method. A portion of these compacted specimens were tested directly after compaction, while others were either soaked or dried and tested after a 24 hour conditioning period in order for the moisture to reach an equilibrium condition.

The last laboratory task completed was the repeated load triaxial tests. A series of unconfined, undrained repeated load triaxial tests was conducted on the four subgrade materials. As in the static triaxial tests, all materials were compacted at target moisture contents and maximum dry densities according to the Standard Proctor method. Some of the compacted specimens were soaked in water and others were left to be dried out and then conditioned for at least 24 hours before testing. Other specimens were tested at their optimum moisture content (OMC) directly after compaction. These moisture levels were the same as the moisture levels achieved for the static triaxial shear strength tests. At least 10,000 loading cycles were applied on each specimen at four different stress ratios. The applied stress levels were taken as percentages of the static failure deviator stress defined by *Mohr-Coulomb*. The traditional Mohr-Coulomb criterion, which has the following form.

$$\tau = C + \sigma \text{ Tan } (\varphi)$$

Where τ is shear strength, C is cohesion, σ is normal stress at failure, and φ is friction angle. The cohesion and friction angle are material properties obtained from laboratory triaxial tests. (9)

The applied loads followed a haversine pulse of 0.45 second loading duration. A one second dwell (delay) was allowed between stress pulses to maximizing recovery of the resilient strain. A minimum of two replicate tests were conducted at each moisture/stress ratio combination.

Results

A rational mechanistic constitutive model for predicting permanent strain of subgrade pavement materials as a function of resilient strain, stress-to-strength ratio, degree of saturation, plasticity index, and percent passing #200 sieve was developed for the four subgrade (cohesive and cohesionless) materials investigated. A major advantage of this model is that it considers both the permanent as well as the resilient strain, which can be directly calculated from multi-layer elastic pavement response models. The goodness of fit statistics of the developed model as well as the residual analysis showed excellent accuracy and low bias. The final developed model is as follows:

$$\begin{aligned} \log(\varepsilon_p/\varepsilon_r) = {} & 0.96452\ (S) + (0.00004\ wPI^2 - 0.00014)(S_r)^2 \\ & + (-0.00493\ wPI^2 + 0.03511)(S_r) + 1.98633\ (wPI^2/S_r) \\ & + 0.16729\ (wPI)^2 - 0.50907\ (wPI) - 1.14655 + 0.12647\ \log(N) \end{aligned} \qquad (16)$$

With n = 3879, Logarithmic: $S_e/S_y = 0.284$, $R^2_{Adj} = 0.92$; and Arithmetic: $S_e/S_y = 0.304$, $R^2_{Adj} = 0.91$.

Where: ε_p = accumulated plastic strain at N repetitions (%); ε_r = resilient strain (%); S = dynamic deviatoric stress/static deviatoric stress ratio; wPI = weighted plasticity index = % Pass #200 * PI/100, S_r = degree of saturation (%); and N = number of load repetitions ($N \geq 50$)

This model follows a power law which can be represented by a straight line in the $\log(\varepsilon_p/\varepsilon_r)$-log N space. As the model shows, the intercept is a function of the stress-to-strength ratio, degree of saturation, plasticity index, and percent passing #200, while the slope is constant for the range of the ADOT subgrade materials investigated in this study. The degree of saturation was incorporated into the model instead of the moisture content for several reasons. The moisture content in a soil can vary greatly from one material to another. In addition, there is no finite maximum value of the moisture content. On the other hand, the degree of saturation has a finite scale from zero to a maximum of 100%. Therefore, any erroneous data that may lead to saturation levels more than 100% can be detected.

An approximate methodology for subgrade rutting prediction using the recommended model was also developed. This was primarily developed to verify the overall implementation reasonableness of the recommended model. It was found that the predicted subgrade rutting values using this method agreed reasonably well with subgrade rutting predicted using the M-E PDG. A correction factor to the predicted rutting from the study was necessary. The average value of this correction factor based on the provisional verification analysis conducted in this research was found to be 1.952. This correction factor was also found to be close to the field calibration factor applied to the M-E PDG subgrade rutting model ($\beta_{M\text{-}E\ PDG} = 1.350$). In addition, the rate of accumulation of the subgrade rutting with traffic repetitions (slope of the power equation) from the developed model was found to agree quite well with that from the M-E PDG.

ENVIRONMENTAL

Project 10: Implementing EICM to Arizona Climatic Conditions

Objective

The objective of Project 10 was to present the Arizona input parameters for the Enhanced Integrated Climatic Model (EICM) module, particularly the environmental parameters needed to define the climatic conditions. Default input climatic files for Arizona conditions were developed and typical climatic zones within the state were proposed. Finally, the software developed to either generate climatic input files or to retrieve the default available data was presented, along with a user guide to the software.

Background

The M-E PDG consists of several computational modules linked by interfaces. Examples of these modules are: a) the thermal cracking module; b) the fatigue module; c) the permanent deformation module; d) the finite element analysis module; and, e) the linear elastic analysis module. This report deals with the EICM module and its implementation to Arizona climatic conditions.

The basic computational unit of the EICM module makes use of the Enhanced Integrated Climatic Model developed by the Federal Highway Administration (FHWA). The methodology is capable of predicting the temperature distribution within a layered pavement system (both AC materials as well as unbound materials) at any time and depth for a given climatic regime, which is then used in subsequent modules' computations.

Another critical role of the EICM module on the pavement performance prediction system deals with the evaluation of the modulus as it is affected by environmental conditions. In this respect, the EICM has the ability to predict changes in moisture content and hence, the corresponding changes in soil matric suction throughout the pavement structure at any time within the future, as well as seasonal climatic variations such as freezing, thawing, and recovery from thawing. This information is in turn used by the EICM to define a set of time and position-varying factors that are needed to adjust the resilient modulus (M_R) in consideration of environmental conditions.

Input Parameters Needed by the EICM Module

A relatively large number of input parameters is needed to run the EICM, ranging from climatic data to boundary conditions to numerous material properties. The exact set of parameters required to be input by the user depends on the hierarchical level (Level 1, 2, or 3) being used. These hierarchical levels were implemented throughout the M-E PDG so that the user could utilize input values, which are consistent with available data and available funds to generate input data. Thus Level 1 typically corresponds to directly measured, site-specific values, which are the most precise. Level 3 typically involves the use of estimated input values, or in the case of material properties for the EICM, values inferred from index properties such as plasticity and gradation. Level 2 analysis involves a combination of Level 1 and Level 3 data.

The EICM needs a complete set of parameters to run, therefore it automatically generates the missing input data when Levels 2 or 3 are used and some of the user input data is missing. The missing data is generated internally within the EICM, using the data that is input by the user and predictive algorithms developed through research.

The input parameters needed by the EICM module can be classified into the following groups:

- Analysis conditions parameters
- Infiltration/drainage conditions parameters
- Structural data parameters
- Material characterization parameters
- Environmental parameters.

This project dealt primarily with the environmental parameters needed to generate the climatic data used by the EICM. The Environmental parameters are those needed to define the climatic conditions of the site being considered. These include the location of the site (latitude and longitude), site elevation, and the depth to the groundwater table (GWT). In addition to being used to define the site location, the latitude is used to calculate the amount of incoming solar radiation on the pavement and the time of local sunrise and sunset. Even though the GWT depth is a boundary condition, it was tied to the Environmental parameters for the sake of model organization.

The Environmental parameters are needed at any hierarchical level, whether it is desired to interpolate climatic data from different stations, or to use the default regional data generated for Arizona.

Climatic Data Needed by the EICM Module
The climatic information needed to run the EICM Module includes air temperature, precipitation, wind speed, and sunshine.

The EICM requires this information each time, if it is to operate properly. The EICM uses hourly data for a 5-year record period. If hourly information is not available, the EICM can generate hourly data by interpolating from daily data for the temperature, the precipitation and the wind speed, without significant sacrifice in accuracy. However, sunshine information must be collected for every time step desired, currently at one-hour increments. Due to the last requirement, only stations that can provide hourly information are of interest to this project.

Climatic Data for the State of Arizona
To calibrate the EICM Module to the Arizona climatic conditions, a search for information on weather stations reporting hourly data was conducted.

Weather Stations with Hourly Climatic Data for the State of Arizona

Several sources were consulted to determine the best set of weather stations that completely covered Arizona. The sources considered included:

- The National Climatic Data Center (NCDC)
- The Federal Highway Administration Long-Term Pavement Performance (FHWA-LTPP) Database
- The Arizona Meteorological Network (AZMET) Database.

After analyzing the data contained in these sources of climatic information for Arizona, it was decided to employ the ASOS (Automated Surface Observation System) stations reported by the NCDC for the coverage it provides. ASOS contains stations with digital data hourly, which is the most important requirement in order to be implemented into the EICM.

Data from 22 stations was collected (14 stations in Arizona and 8 stations from the following surrounding states: Nevada, Utah, Colorado, New Mexico) and implemented into the M-E PDG software. The locations of the stations are depicted in Figure 8.

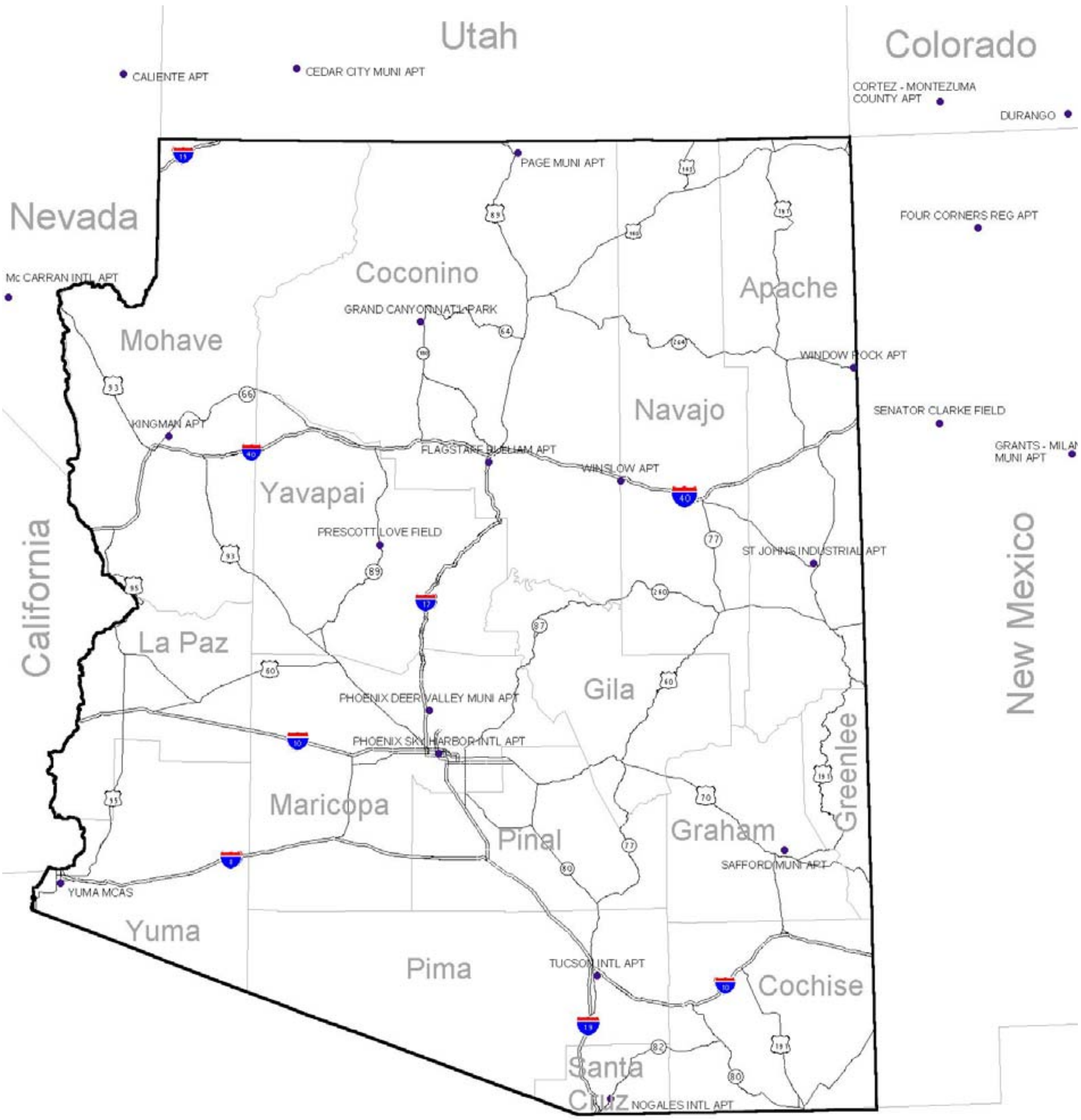

Figure 8. NCDC ASOS Stations Located in Arizona and Surroundings

Climatic Regions of Arizona

The state of Arizona was divided into climatic regions to help the user to decide which station or stations to use for gathering the required climatic information. Different ways to divide Arizona into climatic regions were found in the literature:

1. The NOAA – NCDC climatic division based on county boundaries.
2. The National Weather Service climatic division based on uniform weather conditions during a standard forecast period.
3. The climatic division of the Köppen Climatic System based on elements that correspond to broad regions of natural vegetation, modified by (10) to accommodate the Arizona conditions.
4. Climatic regions based on heating and cooling requirements.
5. Climatic regions based on physiographic units and highway design requirements.

In addition, maps prepared based on precipitation characteristics and elevation contour lines were taken into consideration in making the final climatic division for the state of Arizona.

In 1972, Witczak conducted a study to identify the occurrence and distribution of selected highway design and construction factors in regional geomorphic units for the contiguous 48 U.S. states (11). In this study, a regional classification system was used to produce 97 different Sections throughout the continental U.S. The information gathered to develop these Sections was derived from the sources of physiography (geomorphology), geology, pedology, and climatology as well as from engineering experience.

Climatic factors taken into consideration included: annual precipitation, annual temperature, freezing index, and potential evapotranspiration. The highway design and construction factors used to delimit each section included: availability of quality aggregate resources; soil origin and texture; high volume change soils; potentially poor subgrade support conditions (clayey and organic soils); and frost-susceptibility.

Due to the broad range in characteristics included in the development of the physiographic units presented by Witczak, this work was adopted as the base for developing the climatic regions to be implemented into the EICM module. Precipitation, topography, and Heating and Cooling Requirements maps were subsequently used to further refine the boundary lines shown in the final map. The proposed climatic division for Arizona is presented in Figure 9.

The definition and characteristics of each region can be found in Appendix 10. For each climatic region, either one or several weather stations were assigned. The chosen weather stations can be used to define the climatic characteristics of each region. The information is presented in Table 22.

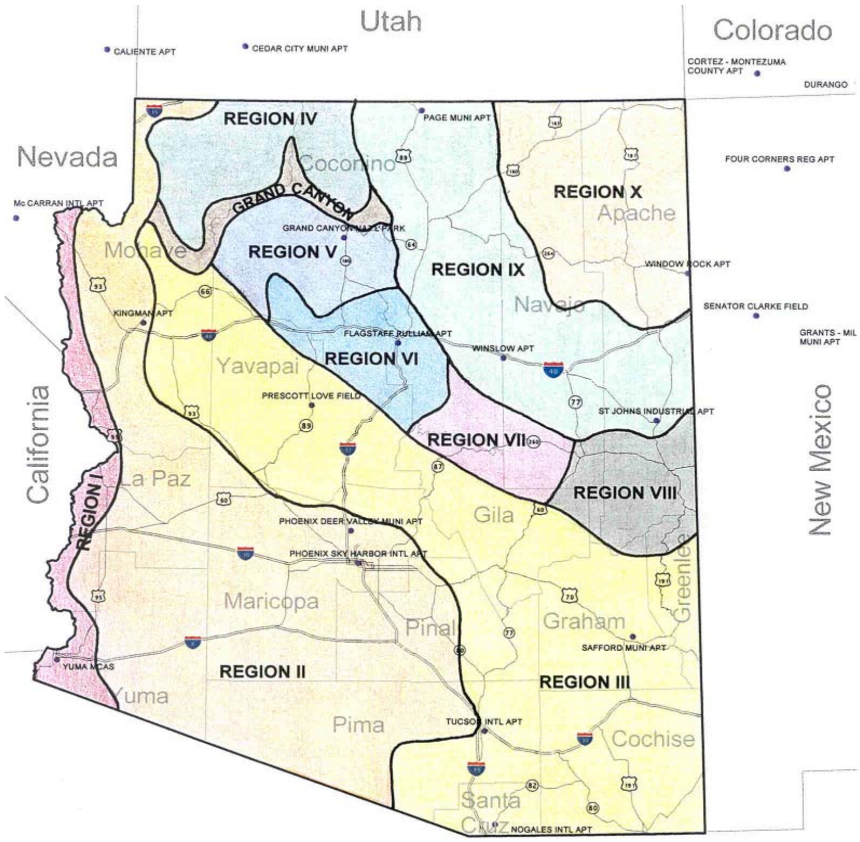

Figure 9. Recommended Climatic Division for the State of Arizona

Table 22. Weather Stations Assigned to Each Climatic Region

Region	Name	Weather Stations
Region I	Colorado River Valley	Yuma MCAS McCarran International Airport Combination of both datasets
Region II	Sonoran Desert	Kingman Airport Phoenix Deer Valley Airport Phoenix Sky Harbor Airport Caliente Airport (northern portion of region)
Region III	Mexican Highland	Prescott Love Field Safford Municipal Airport Tucson International Airport Nogales International Airport
Region IV	Faulted Plateaus	Cedar City Municipal Airport
Region V	San Francisco Plateau (Western Portion)	Grand Canyon National Park
Region VI	San Francisco Mountains	Flagstaff Pulliam Airport
Region VII	San Francisco Plateau (Eastern Portion)	Winslow Airport
Region VIII	White Mountains	St Johns Industrial Airport
Region IX	Navajo	Page Municipal Airport Winslow Airport St Johns Industrial Airport
Region X	Northeast Plateau	Window Rock Airport Colorado and New Mexico stations

Software Developed to Generate/Retrieve the Climatic Input Files Needed by the EICM Module

The software to manipulate the Arizona climatic information was developed. The software comprises the files needed to generate climatic information; storage files for internal calculations; a file containing the list of the weather stations available in the database; a stand-alone program called *Climatic.exe*, which creates the climatic input files needed by the EICM module; and files to store the EICM output required in subsequent modules or for future import use.

The software has the flexibility to allow the user to incorporate, at any time, new weather stations as the information becomes available. The user can select from 1 to 6 weather stations to be used for interpolation of climatic data. It also has a user-friendly interface that helps the user to generate the climatic files needed to run the EICM module.

TRAFFIC

Project 11: Development of Design Guide Traffic Files for ADOT

Objectives

The objectives of this study were (1) to develop a computerized traffic database of the entire Arizona highway network for pavement analysis and design; (2) to implement the traffic database system into the ADOT M-E PDG. In addition, the database system developed may be directly accommodated to the current ADOT Geographical Information System (GIS) for mapping purposes.

Methodology

Four features were included in this study:

a) Average Annual Daily Traffic (AADT)
b) Annual Growth Rate (rg)
c) Percent Trucks (pt)
d) Vehicle Classification Percentage (VCP).

Six interstates, 13 US highways and 86 state highways were included in the AZ highway network. Table 23 presents a summary of the highway network studied in this research. Traffic units were developed based on (1) existing ADOT Highway Pavement Management System(HPMS) traffic sections and Vehicle Classification Percentage (VCP) stations; (2) plots of the detailed AADT as a function of mileposts; and (3) regrouping of the existing class stations into reasonable and homogeneous traffic units according to traffic volume variations (within 10%-15% range).

Interstate Highway	U.S. Highway	8tate Highway
I-8, I-10 I-15, I-17 I-19, I-40	U-60, U-89T, U-180, U-64, U-93, U-191 U-70, U-95, U-191B, U-89, U-160, U-89A, U-163	S-8B, S-10B, S-10X, S-40B, S-40X, S-51, S-61, S-64 S64S, S-66, S-67, S-68, S-69, S-71, S-72, S-73, S-74, S-75, S-77, S-78, S-79, S-80, S-81, S-82, S-83, S-84, S-85, S-86, S-87, S-88, S-89, S-89A, S-79B, S-89L, S-90, S-92, S-95, S-95B, S-95X, S-95T, S-96, S-97, S-98, S-99, S-101L, S-143, S-153, S-169, S-170, S-177, S-179, S-180A, S-181, S-186, S-187, S-188, S-189, S-202L, S-210, S-238, S-260, S-260S, S-261, S-264, S-266, S-266S, S-273, S-277, S-277S, S-280, S-286, S-287, S-288, S-289, S-303L, S-347, S-366, S-373, S-377, S-386, S-387, S-389, S-473, S-564, S-587, S-989
Total: 6	Total: 13	Total: 86

Table 23 Summary of the Arizona Highway Network Studied in this Project

The prediction of the future AADT and its associated annual growth rate (rg), percent trucks (pt) and vehicle classification percentage (VCP), which are based on historical AADT traffic information, have been performed by three approaches:

a) ADOT linear method
b) ASU linear growth method
c) ASU compound growth method.

Results

All the traffic analysis results for the Arizona highway network were tabulated, plotted, and presented in Appendix 11: *Development of Design Guide Traffic Files*. In addition, the traffic database developed was electronically filed in a CD that covers all the results of this research analysis. The CD has been divided in five (5) folders:

1. ADOT raw data
2. Converted raw data
3. Federal route
4. Interstate route
5. State route.

Each folder contains detailed information and graphs that support the analysis. The folders are further subdivided into the following sub-folders:

1. ADOT raw data: The sub-folders are based on the sources used to acquire the data:
   (a) ADOT data1-vehicles
   (b) ADOT data2-adobe The name of the folder
   (c) ADOT data3-from CD
   (d) ADOT data4-ACCESS
   (e) ADOT data5-WIM
   (f) ADOT data6-ESAL
   (g) ADOT data7-% TRK
   (h) ADOT data8-AXLE load

2. Convert raw data: The ADOT raw data was regrouped and converted to a more readable data base:

   (a) ADOT 1-vehicle class
   (b) ADOT 2-ADT (more sub-folders are included for different highway categories)

3. Federal route: One folder, three macros and excel worksheets for plots are included:
   (a) Folder: contains the analysis results for the AADT, r_g, pt and VCP

4. Interstate route: One folder and excel worksheets for plots are included:
   (a) Folder: GIS file- contains the analysis results for the AADT, r_g, pt and VCP

5. State route: One folder, two macros and excel worksheet for plots are included:
   (a) Folder: GIS file- contains the analysis results for the AADT, r_g, pt and VCP

PROJECT SUMMARY

This executive summary presents the final results of the program entitled *Development of Performance Related Specifications for Asphalt Pavements in the State of Arizona*. The ultimate program goal was the implementation of a methodology for Performance Related Specifications for asphalt pavements in the state of Arizona. This goal was not accomplished as it relied upon the Mechanistic-Empirical Pavement Design Guide (M-E PDG) developed for the National Cooperative Highway Research Program, which is still in the process of being calibrated and finalized at a national scale. It is anticipated that the final Version 1.0 Code for the overall M-E PDG program will be completed by 1 January 2007 by NCHRP Contractors.

The overall research program was divided into three major work phases. The Phase I effort was related to the development of the Work Plan. Phase II of the program was related to the development of typical design input parameters for Arizona conditions. Both phases were successfully completed. Phase III dealt with the development of Performance Related Specifications for the state of Arizona. Phase III should be accomplished once the M-E PDG becomes available to assess the nationally calibrated models and enhance/calibrate those models to account for design conditions (traffic, materials of construction, environment) in the state of Arizona.

Phase I and Phase II were divided into eleven (11) different projects. These were:

Project 1: Development of Work Plan
Project 2: ADOT AC Binder Characterization Database
Project 3: ADOT AC Mix Stiffness Characterization Database
Project 4: ADOT AC Thermal Fracture Characterization
Project 5: ADOT AC Mix Permanent Deformation Database
Project 6: ADOT AC Fatigue Characterization Database
Project 7: ADOT Implementation of Simple Performance Test
Project 8: ADOT Unbound Materials Modulus Database
Project 9: ADOT Unbound Materials Permanent Deformation Database and Development of Universal Permanent Strain Model
Project 10: Implementing EICM to Arizona Climatic Conditions
Project 11: Development of Design Guide Traffic Files for ADOT

The final results for each of the projects were summarized and presented in this executive summary. In addition, a CD containing all the delivered final reports and relevant files has been enclosed to this report.

This study has provided ADOT with a comprehensive database that includes material characterizations and properties of all typical materials used within the state, available for use in the state calibration procedure of the newly developed mechanistic-empirical approach.

Project 2: *ADOT AC Binder Characterization Database*, provides ADOT with a database of Superpave-AASHTO properties for six typical AC binders commonly used in ADOT construction projects of HMA pavements. The main binder properties evaluated at four different aging conditions were: penetration, softening point, absolute viscosity, kinematic viscosity, flexural creep stiffness parameters, complex shear modulus, phase angle, and ultimate tensile strains. The characterization of the AC binder properties serves as direct required input to estimate the Master Curve (Complex Modulus-Reduced time) of the specified asphalt mixture.

Project 3: *ADOT AC Mixture Stiffness Characterization Database* provided ADOT with a comprehensive database of the dynamic modulus stiffness properties associated with typical ADOT mixtures. The E* database included the detailed test data, numerically optimized master curves and data required for the Witczak E* predictive model. These properties data are required to implement the pavement design and analysis of the M-E PDG at all analysis levels.

Project 4: *ADOT AC Thermal Fracture Characterization* provided ADOT with a comprehensive database of the thermal fracture properties specifically associated with eleven conventional ADOT mixtures and four asphalt rubber mixes. The database included creep compliance and tensile strength test data at different temperatures. These properties are fundamental material inputs required in the M-E PDG. In addition, energy until failure and total fracture energy results were provided.

Project 5: *ADOT AC Mix Permanent Deformation Database* provided ADOT with a repeated load permanent strain database collected from repeated load dynamic testing. In addition to this comprehensive database collected from thirteen different projects, a model to predict the permanent deformation behavior was developed.

Project 6: *ADOT AC Fatigue Characterization Database* provided ADOT with a comprehensive database of six typical ADOT HMA mixture fracture (fatigue) properties and parameters for use in the implementation of the M-E PDG system. Furthermore, a global fatigue cracking model specific for the ADOT HMA mixtures was developed. This model can be used to predict the fatigue life of any ADOT mix with a high degree of precision.

Project 7: *ADOT Implementation of Simple Performance AC Mixture Test* provided ADOT with a comprehensive field validation of the recommended approach for the Simple Performance Test. A database comprising F_n and F_t data, permanent strain at flow, recoverable strain at flow, $\varepsilon_p/\varepsilon_r$ from F_n test, compliance from F_t test, and mixture data related to all F_n and F_t tests was elaborated under this project.

Project 8: *ADOT Unbound Materials Modulus Database* developed a set of typical k_1-k_3 material parameters for a range of typical Arizona base, subbase and subgrade soil conditions used in Arizona highway construction area. This database was used to calibrate a resilient modulus predictive model for ADOT unbound materials, capable of estimating changes in modulus as a function of changes in state of stress, moisture and density. This model can be use in pavement response models and mechanistic-empirical design methods and fulfills key requirements of accuracy, computational stability and implementability in existing mechanistic-empirical design methodologies.

Project 9: *ADOT Unbound Materials Permanent Deformation Database and Development of Universal Permanent Strain Model* was directed towards the development of a rational mechanistic constitutive model to predict permanent deformation of the unbound subgrade, subbase and base materials provided by ADOT to implement the new M-E PDG for Arizona conditions under dynamic repeated load repetitions. The model developed considers both the permanent as well as the resilient strain, which can be directly calculated from multi-layer elastic pavement response models. The goodness of fit statistics of the developed model as well as the residual analysis showed excellent accuracy and low bias.

Project 10: *Implementing EICM to Arizona Climatic Conditions* provided ADOT with the input environmental parameters needed to define the Arizona climatic conditions for the Enhanced Integrated Climatic Model (EICM) Module of the M-E PDG. Default input climatic files for Arizona conditions were developed and typical climatic zones within the state were proposed.

Project 11: *Development of Design Guide Traffic Files for ADOT* provided a computerized traffic database of the entire Arizona highway network for pavement analysis and design; which included 6 interstates, 13 US highways and 86 state highways. The database system developed may be directly accommodated to the current ADOT Geographical Information System (GIS) for mapping purposes and used in the implementation of the M-E PDG for the state of Arizona.

RECOMMENDATIONS

This project has been a major undertaking to advance the implementation of M-E PDG (Mechanistic-Empirical Pavement Design Guide) practices in Arizona. The individual project studies have led to several recommendations. However, it needs to be recognized that there is absolutely no more significant recommendation than to continue with the primary goal of the original study: Calibration of the M-E PDG process directly to Arizona conditions and the eventual implementation of the new advanced pavement design guide within Arizona.

The Arizona calibration process will not be simple or direct. There are several reasons that this calibration will require special care. Several of the most important considerations are:

- The M-E PDG distresses, used in the model development, for NCHRP 1-37A (further researched in NCHRP 1-40A-D) are heavily dependent upon distress frequencies defined by the LTPP Distress Guide (9). There is very little correlation between the current manner by which distress data is collected by ADOT in its PMS system and the LTPP method. Thus, a significant study would be required.
- ADOT now uses Asphalt Rubber Mixtures on its entire network. This material type is currently not incorporated in the present M-E PDG database. As a consequence, it may be erroneous to use the existing Guide directly for ADOT AR-AC mixtures.
- In addition to AR-AC mixtures, a great deal of Open Graded AR is placed on the surface of ADOT highways as a routine part of the design practice. One of the benefits of such a mix is to effectively “paint over” superficial cracks. This aspect will also have to be filtered into the design / calibration process
- The most advanced moisture prediction scheme, and its impact upon changing the soil strength – modulus – has been built into M-E PDG through the EICM. While the subsystem has been “nationally calibrated” with pavement sections across the U.S., there is a very serious lack of datapoints that are characteristic of the severe site weather conditions of the Southwest. It is recommended that special sub-studies be completed to improve the accuracy of the EICM subsystem for Arizona conditions.
- While the current M-E PDG is based upon the analysis of traffic axle-load spectra, ADOT is not equipped to use this form of input for the traffic analysis. All of the ADOT traffic data used in the current ADOT pavement design methodology utilizes 18 Kip ESAL repetitions. This needs to be rectified in the immediate future by ADOT.

In summary, it will be critical to move forward, as a very high priority, with the re-calibration of the M-E PDG system for ADOT conditions.

In addition to pursuing the "big re-calibration" picture, the individual projects also give some significant recommendations to further take advantage of the major and comprehensive research work that has already been completed.

The AC Binder Testing was completed very early in the project. Furthermore, this testing was only completed on six typical ADOT binders. This database must be increased as it is a vital input parameter for performance prediction in the Design Guide. It is recommended that at least four new binders a year be evaluated for a period of at least three years. ADOT should focus on selecting binders that are "new" and/or modified.

It is not recommended that any effort be expended to increase the E* mix database for conventional HMAC mixtures used in Arizona. At present, there is a very large and comprehensive database for these conventional mix categories. In contrast, it is recommended that a high priority effort be undertaken to expand the E* mix database associated with AR-AC and asphalt rubber-asphalt concrete friction course (AR-ACFC). It needs to be recognized that these ADOT mixtures will be the "norm" in the performance prediction models. It will be absolutely mandatory to have this category of ADOT mixtures accurately characterized.

AC thermal fracture (TF) is not a significant distress mode in Arizona. As such, there is no significant need to expand the current AC TF database to any major extent. However, the research that is highly recommended is to continue the development of an advanced methodology to truly characterize the thermal fracture resistance of AC mixtures. Continued work in evaluating the use of total energy as a more rational methodology for thermal fracture must be pursued. This entire process is critical in that an approach must be found that will clearly emphasize the beneficial thermal fracture characteristics of asphalt rubber mixtures compared to conventional HMAC. At present, lab and theoretical modeling studies will show no difference in predicted performance. In contrast, actual field sections clearly demonstrate the advantages of the Asphalt Rubber mixtures.

There still remains a great deal of fundamental research to be pursued in the area of fatigue fracture (cracking) of AC mixtures. This is clearly an area where a number of test results in a fatigue database are typically inadequate. In addition to enlarging the database, there are other significant research issues dealing with the implementation of energy approaches to predict distress. In summary, a rather sizeable fatigue study could be warranted at this point. However, it is strongly recommended that the immediate (short term) research of any project initiated in the calibration effort be totally concentrated on the calibration of the existing M-E PDG fatigue models currently in the Design Guide.

It is recommended that continuous research be conducted to improve the knowledge of AC Mix Rutting Resistance, and pursuit of the Fn test as a viable approach for the permanent deformation of AC mixtures. It is recommended that a large number of additional "AC" and "AR-AC" mixtures be continuously evaluated over the next few years. Results of the Flow Number test should be used to build a database that can eventually build predictive models of the intercept and power values to be functions of specific AC mixture properties.

The scope of this study called for an evaluation of a limited number of subgrade, subbase and base materials for their elastic and permanent deformation response characteristics. It is clear that it will be imperative to evaluate a much broader range of material types. In addition to conducting only lab testing of the elastic and permanent strain characteristics, a series of broader research studies needs to be conducted in the field (e.g., ADOT correlations of in-situ soil/base properties to the Dynamic Cone Penetrometer (DCP) response; assess non destructive testing back calculated to determine the resilient modulus (M_r) and then compare it to the other available predictive models. This entire area of unbound material characterization research should be given a high priority.)

The recommendations in the environmental portion of the study are quite emphatic. The system's breakdown of unique "environmental areas" within Arizona needs to be addressed.

Without question, the biggest gap between ADOT technology and the requirements of the new M-E PDG deal with the entire area of traffic (input and implementation). The key traffic variables in the new Design Guide require the use of actual traffic – axle type-axle load distributions (e.g. Traffic Axle Load Spectra). Arizona is probably one of the worst states at being able to comply with the new Design Guide traffic input. In fact, normal loadometer studies have almost stopped in the last 15 to 20 years. If ADOT is genuinely concerned about gross improvements in its traffic, it will have to immediately implement a traffic study (across the entire traffic network) that will start collecting data on traffic volume, axle types, repetitions by axle load within a given axle type, breakdown by vehicle classification, etc., that will provide sufficient required input for the M-E PDG.

Finally, a major research effort was completed on Traffic in the original report. This study, consolidating key traffic variables as a function of milepost along every highway in Arizona, was compiled for the ***ENTIRE*** network of its highways. It is highly recommended that this traffic database be placed on a GIS so that it can be used by the ADOT Pavement Design Group.

In conclusion, there are many significant research efforts that have been presented and should be carefully reviewed by ADOT. This report has been a landmark endeavor into an unknown future of Pavement Design and Evaluation, based upon radically new "mechanistic" approaches, compared to the old empirical ways that the profession has handled pavement issues.

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